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A.S.M.E.
FUELS DIVISION
ISSUE

COMBUSTION

VOLUME FOUR—NUMBER TWELVE • VOLUME FIVE—NUMBER ONE

CONTENTS

FOR JUNE-JULY 1933

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The four papers listed above will be presented by the Fuels Division of the A.S.M.E. at the semi-annual meeting of the Society, Chicago, June 25-July 1. They are preprinted in this issue of COMBUSTION by permission of the A.S.M.E. The two following Fuels Division papers, also to be presented at the Chicago meeting, will be published in the August issue of COMBUSTION.

Progress in the Removal of Sulphur Compounds from Waste Gases, by H. F. Johnstone, University of Illinois

Standby and Reserve Operation of a Pulverized Fuel Plant by E. H. Tenney, Union Electric Light & Power Company

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ENGINEERING WEEK—CHICAGO, June 25-July 1

Doubtless no larger, more important or timely gathering of engineers has ever taken place than will occur in "Engineering Week" of the Century of Progress.

This week has been officially designated as the time for the meetings of some twenty engineering and scientific societies and for the Sixth Mid-West Engineering and Power Exposition. It is expected that a great many members of these various societies will take their vacations at this time in order to attend the meetings of their respective groups and also see the widely publicized attractions of the Century of Progress. A large attendance at the meetings is assured by the outstanding quality of the programs that have been developed by the various societies.

The A.S.M.E. has planned the largest technical program in its history and every member of the Society who can possibly arrange to be present will find it well worth while to do so. Because of the unusually large number of papers scheduled the Society has asked for the cooperation of various technical journals in making these papers available in printed form. COMBUSTION is glad to have the opportunity of assisting in this important work and is presenting, in full, in this issue four of the valuable papers prepared for the Fuels Division program. In order that this issue may serve most satisfactorily the needs of the Society, it is published in advance of its usual date so that copies will be available for the use of discussers and those attending the meeting.

Two of the remaining four Fuels Division papers will be published in the August issue of COMBUSTION but preprints will be made in time for use at the meeting. The two Fuels Division papers not to be published in COMBUSTION were printed in the May issue of the Society's journal *Mechanical Engineering*. Programs of the Fuels and Power Divisions and a selected list of papers from other programs, which are of interest to COMBUSTION'S readers, are given below. All meetings will be held at the Palmer House.

FUELS DIVISION

FUELS (I) Monday, 9:30 a.m., Red Lacquer Room

Presiding Officer: R. A. Sherman, Chairman, A.S.M.E. Fuels Division; Battelle Memorial Institute, Columbus, Ohio.

A Century of Progress in Fuel Technology, O. P. Hood, Chief, Technologic Branch, Bureau of Mines, U. S. Department of Commerce, Washington, D. C.

FUELS (II) Monday, 2:15 p.m., Red Lacquer Room

Presiding Officer: W. L. Abbott, Past-President A.S.M.E., Chief Operating Engineer, Commonwealth Edison Co., Chicago.

Standby and Reserve Operation of a Pulverized-Fuel Plant, E. H. Tenney, Chief Engineer of Power Plants, Union Electric Light & Power Co., St. Louis.

Oil Firing in Pulverized-Coal Furnaces, James F. Muir, Mechanical Engineer, Montaup Electric Co., Somerset, Mass.

FUELS (III) Tuesday, 9:30 a.m., Room 404

Presiding Officer: G. F. Gebhart, Armour Institute of Technology, Chicago.

Correlation of Grindability with Actual Pulverizer Performance, Martin Frisch, Foster Wheeler Corporation, New York, and G. C. Holder, Chief Chemist, Foster Wheeler Corporation.

The Principles of Underfeed Combustion and the Effect of Preheated Air on Over- and Underfeed Fuel Beds, P. Nicholls, Supervising Engineer, Fuels Section, U. S. Bureau of Mines, Pittsburgh Experiment Station, Pittsburgh, and M. G. Eilers, Associate Fuel Engineer, U. S. Bureau of Mines Pittsburgh Experiment Station, Pittsburgh.

SMOKE ABATEMENT Tuesday, 2:30 p.m., Ballroom

Presiding Officer: Ely C. Hutchinson, President, Edge Moor Iron Co., Edge Moor, Del.

The Measurement of Properties of Cinders and Fly Ash, Arthur C. Stern, Research Instructor in Smoke Abatement, Stevens Institute of Technology, Hoboken, N. J.

Progress in Removal of Sulphur Compounds from Waste Gases, H. J. Johnstone, Department of Chemistry, University of Illinois, Urbana, Ill.

The Human Side of Smoke Abatement, William G. Christy, Secretary, A.S.M.E. Fuels Division, and Smoke Abatement Engineer, Department of Smoke Regulation, Hudson County, Jersey City.

POWER DIVISION

INDUSTRIAL POWER Thursday, 9:30 a.m., Ballroom

Presiding Officer: Will J. Sando, Advisory Engineer, Reconstruction Finance Corporation, Chicago District, Chicago.

Application of High-Boiling-Point Organic Compounds to Industrial Heat-Exchange Problems, J. J. Grebe, Director, Physical Research, Dow Chemical Co., and E. F. Holser, Engineering Department, Dow Chemical Co., Midland, Mich.

A Graphical Method for the Design of Flexible Members for Steel Piping, E. A. Wert, Piping Division, Detroit Edison Co., S. Smith, Piping Division, Detroit Edison Co., and E. T. Cope, Research Department, Detroit Edison Co., Detroit.

CENTRAL-STATION POWER (I) Friday, 9:30 a.m., Ballroom

Presiding Officer: John M. Drabelle, Mechanical and Electrical Engineer, Iowa Railway & Light Corp., C. R. & I. C. Railway Co., Cedar Rapids, Iowa.

Performance of Two 101,000-Sq. Ft. Surface Condensers, J. N. Landis, Assistant Mechanical Engineer, Brooklyn Edison Co., Brooklyn.

Surface-Condenser Design and Operating Characteristics, Townsend Tinker, Ross Heater and Manufacturing Co., Buffalo.

A Thermal Study of Available Steam-Power-Plant Heat Cycles, G. A. Hendrickson, Engineer, Detroit Edison Co., Detroit, Mich., and S. T. Vesselowsky, Engineer, Detroit Edison Co., Detroit.

CENTRAL-STATION POWER (II) Friday, 2:15 p.m., Ballroom

Presiding Officer: Alex D. Bailey, Manager, A.S.M.E., Superintendent of Generating Stations, Commonwealth Edison Co., Chicago.

Characteristics of Large Hell Gate Direct-Fired Boiler Units, W. E. Caldwell, Research Engineer, United Electric Light & Power Co., New York.

The Study of Calcium-Sulphate Scale Prevention at Higher Steam Pressures, F. G. Straub, Professor of Special Research, University of Illinois, Urbana, Ill.

Moisture Problem in Steam Turbines, C. Richard Soderberg, Manager, Turbine-Apparatus Division, Westinghouse Elec. & Mfg. Co., South Philadelphia.

BOILER FEEDWATER Monday, 9:30 a.m., Room 10

Presiding Officer: S. T. Powell, Chairman of Feedwater Studies Committee, Consulting Engineer, Baltimore.

The Effect of Suspended Solids. Progress Report of Subcommittee No. 3 on Priming and Foaming, of the Joint Research Committee on Boiler Feedwater Studies, C. W. Foulk, Chairman of Subcommittee.

Three additional subcommittee reports.

PULVERIZING AND DUST Tuesday, 2:30 p.m., Room 14

Relation between Pulverizer Capacity, Power, and Grindability, R. M. Hardgrove, Engineer, Babcock & Wilcox Co., New York.

Characteristics and Mitigation of Industrial Dusts, J. M. DallaValle, Assistant Sanitary Engineer, Public Health Service, Washington, D. C.

SCIENCE AND ENGINEERING Tuesday, 8:00 p.m., Ballroom

Industrial Developments of the Century, A. P. M. Fleming, Manager of Research and Education Department, Metropolitan-Vickers Electrical Co., Manchester, England.

HYDRAULIC AND WATER POWER (II) Thursday, 2:15 p.m., Ballroom

Resume of the Engineering Reports on the St. Lawrence Power Development, Daniel W. Mead, Hydraulic and Sanitary Engineer, University of Wisconsin; and Thomas H. Hogg, Chief Hydraulic Engineer, Hydroelectric Power Commission of Ontario, Toronto, Ontario.

Discussion of St. Lawrence Waterway.

ECONOMICS Friday, 8:00 p.m., Red Lacquer Room

Some Fundamental Problems of the Engineer, Dr. F. B. Jewett, Vice-President, American Telephone & Telegraph Co., New York.

The Internationalization of Scientific Knowledge as a Factor in World Economic Recovery, A. P. M. Fleming, Manager of Research and Education Department, Metropolitan-Vickers Electrical Co., Manchester, England.

Oil Firing in Pulverized Coal Furnaces

By JAMES F. MUIR[1]

A large number of coal burning stations have been changed to oil firing in order to take advantage of low cost oil fuel. This paper includes a detailed description of the work done in connection with the conversion of a few representative pulverized coal installations. Individual features discussed include the following: Plans for the replacement of coal burning systems, revamping of cylindrical type, fan tail and intertube burners to permit the installation of oil firing units, experiments with vertical firing of oil with steam and mechanical atomizers, and successful development of vertical downward firing with mechanical atomizing burners in combination with fan tail coal firing units. The situation surrounding these activities is summarized under "General Comments and Conclusions."

THE availability of fuel oil during the past few years at prices below the corresponding heat unit price level of coal has resulted in the changing of a large number of steam generating plants from coal to oil firing. Many of these stations were considered as being located beyond the range of fuel oil markets and were designed and equipped for the burning of coal only. Through the foresight of the designers, a few plants which were built before the commercial development of combination burners, were provided with furnaces suitable for either coal or oil burning. A change from solid to liquid fuel, in some of these cases, necessitated the blanking off or the entire removal of the coal burning equipment and installation of separate oil burners. In other instances the coal burners were modified to accommodate oil guns, some of these revamped units permitting the firing of both fuels simultaneously.

The firing of oil in pulverized coal burning furnaces equipped with horizontal cylindrical type coal burners presents a relatively simple and low-cost undertaking. On the other hand, intertube type and fan tail burner installations give rise to economic as well as engineering problems because the dismantling of expensive coal burner equipment and costly changes in water-cooled walls have to be taken into consideration. The methods employed by a few representative plants in coping with these problems and subsequent developments, together with the work done in revamping burners and the performance results obtained, are set forth in this paper.

Oil Firing with Calumet Coal Burners and Vertical Oil Firing with Vertical Coal Burners at the Montaup Electric Company's Somerset Station

The steam plant equipment of the Montaup Electric Company's Somerset Station consists of five Stirling boilers, which deliver steam to the turbine header at 375-lb. pressure and 725 fahr. temperature. The first three of these five combustion units, which are identified as numbers 1, 3 and 5, began commercial operation in October 1925 with horizontal fuel oil firing. Combination burners had not been developed and despite the fact that oil was the most economical fuel for combustion at that time, the three furnaces, which are of air-cooled refractory construction, were designed to permit the future installation of vertical pulverized coal firing equipment. Water screen tubes across the top of ash pits and pulverized coal bunkers were also provided for the purpose of taking advantage of anticipated favorable coal prices.

In 1927 it became necessary to provide additional capacity. The fuel situation, as it prevailed at that time, warranted the installation of coal handling and pulverizing equipment. Accordingly, the horizontal oil burners in service with the three existing boilers were replaced with the Lopulco vertical coal firing system. The two new boilers included in the extension Nos. 2 and 4, were each equipped with furnaces of water-cooled construction and with four Calumet intertube coal burners, but with no provision for oil firing.

After only a few months of operation with pulverized coal, the price relationship of coal and oil was reversed. With the occurrence of this somewhat unexpected fuel market condition, it was decided to provide equipment for firing either coal or oil in all five boilers, if a satisfactory arrangement could be worked out.

This program presented no engineering or constructional difficulties in the case of the three original boilers because, as already mentioned, these boilers, although burning coal, had previously been fired with mechanical atomizing oil burners and the oil firing equipment, which had been previously removed, was of course available for reinstallation.

The later boilers, Nos. 2 and 4, with their water walls and Calumet burners, however, involved a new problem in combination coal and oil firing, if the installation was to be done at a reasonable cost and without disturbance of the new high cost coal burner installation which had been in service less than a year.

After various schemes were considered, it was decided to try burning oil continuously through the ignition openings located below the nozzle of each of the intertube burners. The fuel oil guns used for coal ignition purposes were fitted with relatively small spray plates, capacity of each 340 lb. per hr. at 200-lb. pressure, and put in continuous service. No difficulty was encountered and combustion of oil in combination with pulverized coal was satisfactory. The spray plate and tip was later replaced with a much larger size, capacity of each 900 lb. per hr. at 200-lb. pressure, with equally successful results. Performance with this initial combination arrangement was so satisfactory that it was decided to attempt a further step in this same direction to increase oil burning capacity. This involved the placing of mechanical atomizing oil burners through the secondary air ports of the coal burners.

There are three 9-in. by 4-in. air openings on one side and four on the other of each Calumet burner. By installing two oil burners in the upper and lower of the three air openings on one side and a like number in the two center of the four openings on the other side, a staggered arrangement of oil firing units

[1] Mechanical Engineer, Montaup Electric Co., Fall River, Mass.

and air supply ports was obtained. The installation finally consisted of five oil firing units, two on each side and one at the bottom of each of the Calumet coal burners. (See Fig. 1.)

The secondary air ports are each equipped with individual dampers connected with a device for operating in unison the seven dampers on each burner. The four dampers in contact with oil guns are slotted to permit operation of these air control units when burning oil. Secondary air for the oil burner installed through the coal ignition sleeve is supplied through longitudinal slots in the sleeve, which consists of a 4-in. pipe. A rotating outer sleeve with corresponding slots serves as a damper and is provided primarily for shutting off the flow of air when burning coal.

The oil units are not equipped with air deflectors or propellers and, therefore, when firing oil, proper mixing of atomized fuel and air is dependent upon the secondary air as it is delivered through the coal burner air ports, and upon primary air delivered through the coal burner nozzle. The system of air supply for oil firing it will be noticed is the same as that used for the Calumet coal burners. Directing the atomized oil mist diagonally across the furnace opening of the coal burner from both sides, results in satisfactory mixing of air and fuel in the furnace and turbulence is accomplished close to the burner. The flame is not particularly short or bushy, dark spots are not in evidence and no furnace pulsation, secondary combustion or smoke with oil firing are noticeable under normal ratings.

For normal operation the oil firing units used are B. & W. No. 32-15 each of which has a capacity of 900 lb. oil at 200-lb. pressure, except in the two guns which are directed toward the side walls. These are equipped with B. &. W. No. 40-20 spray plates, each having a capacity of 700 lb. oil at 200-lb. pressure. The smaller capacity plates are used in these locations to avoid the possibility of impingement on side walls.

The primary air fan is constant speed, and the pressure and volume of air discharged through the coal burner slot are controlled by damper from the boiler control board. This air supply represents about 20 per cent of the total air required for combustion at base load rating of 200,000 lb. per hr.

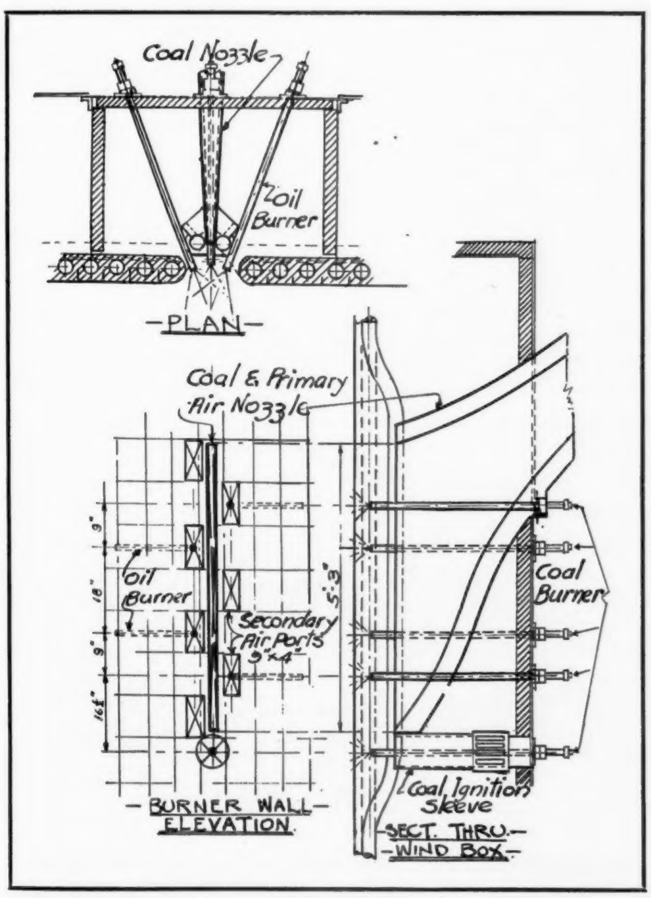

Fig. 1—Oil firing arrangement with Calumet coal burner, Montaup Electric Company, Somerset Station.

In attempting the burning of oil without primary air, the flame reached the tube bank and the lower part of the furnace was entirely free from active combustion. The direction of the column of primary air discharged by the coal slot is downward toward the lower section of the bridge wall and, when used with oil firing, results in utilization of the entire lower part of the furnace and a considerable portion of the ash pit.

With a total of 20 oil firing units per boiler, a maximum of 250,000 lb. of steam per hr. is generated, corresponding to about 550 per cent rating, which is about the same maximum developed with pulverized coal by the four Calumet burners. With oil, this rating can be maintained for an extended period, but with coal slagging trouble limits greatly the operating period at maximum rating. There is no appreciable difference in boiler efficiency, at normal ratings, between oil and coal burning and a change from one fuel to the other can be made almost instantaneously.

The furnaces of the boilers in the Somerset Station are relatively large in volume, 12,500 cu. ft., and heat liberation at normal rating of 200,000 lb. per hr. is approximately 20,000 B.t.u. per cu. ft. per hr., which may be considered relatively low for complete water-cooled furnaces. The large furnaces and conservative rate of heat liberation no doubt contribute largely to the success of the home-made horizontal oil firing installation which has now been in operation for about three years.

The bin system of pulverized coal has also been an important factor in providing an emergency and reserve supply of pulverized coal independent of the coal preparation plant operating schedule. Pulverizers can be operated at off peak periods and run at maximum capacity until the bins are full. Incidentally, it has been found that the preheater tubes keep clean for a longer period when a small quantity of coal, ranging from 10 to 15 per cent of the total fuel, is burned in combination with the oil, and corrosion of the preheater tubes is retarded to some extent. Furthermore fused ash particles, released by the burning of the coal under this schedule, cover the Bailey blocks with a thin layer of slag. The slag coating serves as a protective surfacing against possible impingement and prevents formation of ferrous sulphide on the cast-iron blocks.

Vertical Firing of Oil. It was stated that the changing of boilers Nos. 1, 3 and 5 in the Somerset Station from one firing system to the other presented no engineering or constructional difficulties. However, a change in fuel with two separate types of burners, one for vertical coal firing and the other for horizontal oil firing, necessitated the removal of one set of units and installation of the other. Replacement of burners and auxiliary equipment with furnace alterations, interrupts normal plant operation, and the necessity of undertaking a construction job whenever a change in fuel is warranted is an unsatisfactory and expensive procedure.

These factors and other economic considerations made it desirable to equip these three boilers with combination burners of a type that would permit the firing of oil or coal separately or simultaneously and permit making of the switch at any hour of the day.

A comparison of the operating results which had been obtained with the horizontal mechanical atomizing oil burners and with the vertical coal burners indicated that in the matter of combustion efficiency, steaming capacity and maintenance, and the amount of furnace volume utilized, vertical firing appeared to present the most favorable possibilities. The furnaces are high and wide but relatively shallow between front and bridge walls; mean height between the water screen and arch 24 ft., average depth 16.8 ft. and width 29 ft. At normal capacity of 138,000 lb. per hr., heat liberation is about 14,000 B.t.u. per cu. ft. per hr. which rate would be adjudged normal for an air-cooled setting. The front bank of boiler tubes

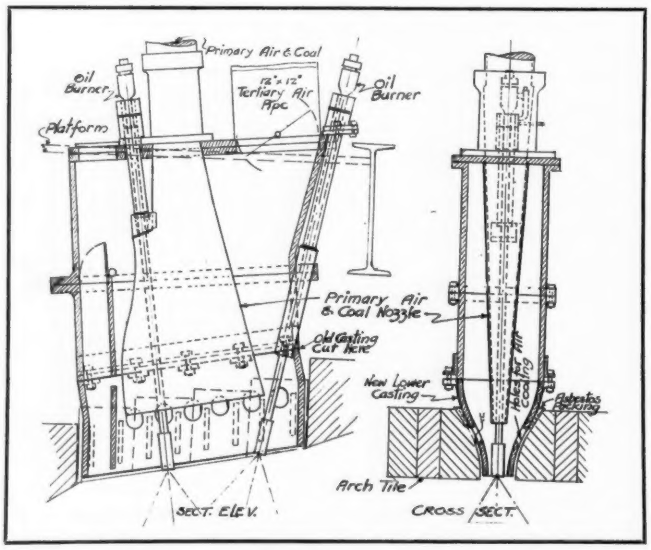

Fig. 2—Vertical combination burner, Montaup Electric Company, Somerset Station.

faces the front wall. Taking all of these factors into consideration it was our opinion that the furnace design and the arrangement of boiler tubes exposed to the furnace were best suited to the flame shape and combustion requirements of vertical firing. In the Somerset Station we already had experience in operating vertical coal burners, but to our knowledge there were no vertically oil-fired, power station furnaces in commercial operation and all available oil burners were designed for horizontal firing. Despite this fact, the vertical firing of oil did not seem particularly radical, so we proceeded with the scheme which contemplated the revamping of existing vertical coal burners in preference to the installation, at almost prohibitive cost, of new combination horizontal firing units.

The vertical fan tail coal burner consists of a two-section rectangular casting 12 in. wide, 25 in. long and about 44 in. high. This casting serves as a housing for the fan-tail unit and for tertiary air ports located parallel and adjacent to the coal nozzle. These tertiary ports are constructed with curved castings which together terminate by forming a rectangular furnace opening, about $2^1/_4$ in. by 24 in., located about $7^1/_2$ in. below the coal nozzle.

The lower sections of the burner housing were redesigned and openings and fittings added to the upper castings to accommodate two mechanical-atomizing, oil firing units. The atomizing tips were located about 13 in. apart at the coal burner outlet. (See Fig. 2.) Small curved vanes located alternately on either side of the burner opening were also added in order to break up into separate sections the solid flat stream of air discharged by the fan-tail nozzle. These vanes are small curved castings so designed that the tip of the vane is located about on the horizontal center line of the burner opening. One vane directs a section of the air stream to the right, the next to the left, alternately across the longitudinal axis of the burner outlet. As a matter of fact the purpose of the vanes is twofold; first, to divide the air discharged into several separate streams and second, to give each sectionalized stream of air, or air and coal, a slight rotary motion as it travels downward through the furnace.

In describing these actions, reference has been made to the air stream from the fan-tail nozzle. It should be explained in this connection that the three systems of air, originally employed for coal firing, are also used with the oil burning system. Primary air only is discharged through the fan-tail nozzle when firing oil. Tertiary air is supplied from the forced draft system through the burner housing, and delivery to the furnace is accelerated by the draft action of the higher velocity stream of primary air. Secondary air after flowing through the wall cooling passages of the setting is discharged to the furnace through openings in the front wall. In a revised design of this same burner (see Fig. 3) which we have developed for the water tube arches, all air required for combustion will pass through the burner, but with air-cooled settings it is necessary of course to maintain air circulation through the wall passages.

The vertical firing of oil, although a departure from the accepted method of firing liquid fuel, has in our case resulted in improved combustion, an increase in steaming capacity and a considerable reduction in furnace maintenance. These favorable results have been accomplished despite the fact that atomizers are operated without diffusers. Saving in maintenance is accounted for by the fact that side walls are subject to impingement and erosion at a location between 13 and 15 ft. from the burner, representing the point of maximum flame spread with horizontal oil firing. The flaring back or recoil of the flame developed by the horizontal burner causes damage necessitating frequent repairs to the burner walls, and diffusers require frequent replacement. With horizontal firing, it is necessary to protect the water screen tubes with flat tile, the replacement cost of which amounts to about $1600 per year for three boilers. With vertical firing, protection of water screen tubes is not required, and after 12 months of operation no furnace repairs or burner replacements have been necessary.

Flame control is the essential element, in fact, the secret of efficient vertical oil firing, and is a function apart from turbulence and mixing of fuel and air. In the Somerset Station vertical oil firing system, the fan-tail nozzle is the flame control unit, and the control medium is primary air. The primary air fan, which was originally provided to operate in conjunction with the coal burners and feeders, together with coal burner connections are used intact for oil firing. The primary air fan delivers from 10 to 20 per cent of the total air for combustion and develops pressures up to 20 in. of water, although only 2 to 3 in. are normally required at the flame control nozzle. These relatively low pressures make possible a controllable range of 10 to 22 ft. in flame length.

The adoption of a fan-tail unit with a relatively long narrow slot for air supply, in combination with a circular cone of atomized oil, would seem to be an unsatisfactory combination. To all intents and purposes for oil firing a circular burner should give the most efficient mixture, but with oil firing the mixing is done in the furnace. Furthermore the weight of the fuel is only about 6 per cent of the weight of the air required for combustion, and the relative volumes, of course, are still further apart. Consider also that the fuel and air are discharged from a pressure system into a large chamber under a slight vacuum, an operating condition which results in a great expansion of air and fuel masses and an unrestrained liberation of volatiles causing oil particles and air molecules to fly in all directions. Practically all of the potential energy in the oil stream is used

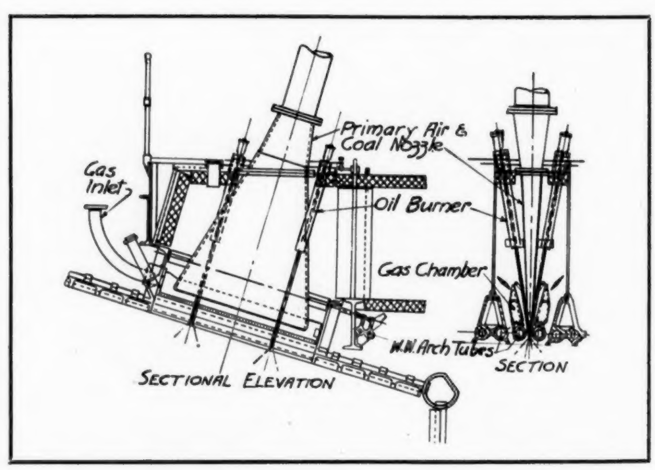

Fig. 3—Vertical intertube burner for coal, oil and gas firing, Montaup Electric Company, Somerset Station.

up in atomization and therefore, the oil, having no directional resistance, is easily and quickly drawn into the air stream. The intensity of these actions is sufficient to meet the requirements of quick ignition and make possible the successful application of the rectangular air slot arrangement for oil burning.

Horizontal Coal Burners Equipped with Oil Firing Units at the Public Service Electric & Gas Company's Burlington Station

Recent designs of steam generating furnaces, generally, permit the changing from one fuel to another without reconstruction and undue interruption in steam generation. These furnaces may be equipped with combination burners or, in the case of coal burning installations, with burners of a type and construction that can readily be converted from solid to liquid firing units. Under the latter classification is included the 650 lb., 850 fahr. boiler installation completed last year by the Public Service Electric and Gas Company at Burlington, N. J. The furnace of this unit, although equipped with horizontal burners designed for pulverized coal firing only, was converted to a fuel oil burning system by means of a comparatively simple change in the coal burner equipment and without change in furnace construction or air supply systems.

The coal burners are of the Combustion Engineering Corp. R-3-29 type, which is of the usual cylindrical form, and the only change made in the coal unit assembly was the substitution of a new head for the primary air nozzle. The original head carried a 5-in. pipe in the center of the nozzle which served as a peep hole for observing burner action. The new head is fitted with a 3-in. pipe in the same central position which serves as a guide sleeve and support for the oil burner barrel. A diffuser cone is attached to the end of the 3-in. pipe. When changing from oil to coal, the oil firing unit is removed and the 3-in. pipe is pulled away from the furnace far enough to remove the diffuser from the path of the primary air. (See Fig. 4.)

The furnace, with a volume of 24,800 cu. ft., is of fin-tube water-wall construction with a water-screen cooled ash hopper. Eight burners are provided, each having a maximum capacity of 7250 lb. of coal per hr., corresponding to a furnace heat liberation of about 28,000 B.t.u. per cu. ft. per hr., at a CO_2 rate of 15 per cent. With oil firing, the corresponding figures at maximum capacity are 5700 lb. of oil and 32,000 B.t.u. Air for combustion is heated to 500 fahr. at maximum load.

The boiler, which is of the Walsh & Weidner cross-drum, sectional-header type with 30,300 sq. ft. of heating surface, has a steaming capacity of 550,000 lb. per hr. with coal and 610,000 lb. with oil. This increased capacity and the fact that combustion efficiency with the oil is equal to the best value obtained with the original coal system demonstrate the adaptability of the same furnace of modern design for either coal or oil firing. It might be inferred also that cylindrical-type pulverized coal burners of the latest designs can be revamped at a more or less insignificant cost and fitted with oil firing units with the expectation of satisfactory results in performance and capacity.

Oil Firing through Top Arches with Steam and Mechanical Atomizers at the Narragansett Electric Company's South Street Station

Fuel oil for steam generation was in use in the Narragansett Electric Company's South Street Station for many years before the recent activity in oil firing installations. In fact in 1920, 28 boilers were equipped with oil firing units, this being the first commercial application of the Lodi mechanical atomizing burner. A few years later the original stoker installations in twenty of the boilers were again put in operation while eight were equipped with pulverized coal systems. The latter group remained in service until 1931 when oil again supplanted coal.

The 1925 extension of South Street Station included the installation of four B. &. W. cross-drum boilers each having a capacity of about 195,000 lb. per hr. of steam at 375 lb. pressure and 640 fahr. temperature. The furnace of boiler

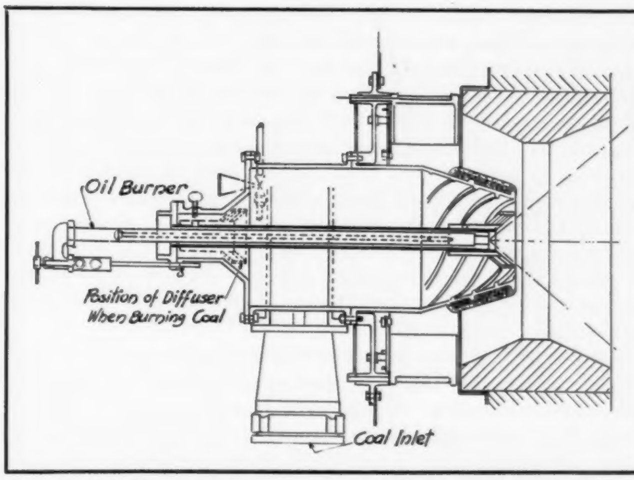

Fig. 4—Oil firing arrangement with Combustion Engineering Type R-3-29 coal burner, The Public Service Electric & Gas Company, Burlington Station.

No. 34 of this group was subsequently reconstructed and the capacity of this unit thereby increased to 250,000 lb. per hr. These four units, because of their large-capacity, modern furnace construction and higher operating economy compared to those in the older section of the plant, are used to carry the base steam load.

At the time of this major addition, coal prices had receded below the equivalent prices of oil, and, from fuel market conditions prevailing at that time, the use of oil fuel seemed a very remote possibility. The new boilers were therefore designed and equipped for coal burning with no expectation that oil would be a successful fuel competitor in the course of a few years.

The pulverized coal firing system in each boiler consisted of eight Lopulco burners inserted in a short refractory arch. The furnaces are alike with water-cooled side and rear walls, Boiler No. 34 also being provided with a water-cooled front wall and slag screen. About 40 per cent of the air required for combustion was carried by air lanes in the side walls and entered the furnace through ports in the front wall at about atmospheric pressure. Primary air, amounting to between 18 and 24 per cent of the total air, was delivered through the 5-in. pipes carrying coal to the burners, the necessary pressure being obtained by small booster fans which drew hot air from the downtakes at the rear of the boiler. Tertiary air was admitted at atmospheric pressure through doors in the burner housings. A furnace draft of about 0.08 in. was maintained.

Preliminary studies indicated that conversion of these four boilers for oil firing, along the more or less conventional lines accepted as good practice, would involve an expenditure which could only be justified by a considerable differential in favor of oil through a continuous period of three or more years. That differential appeared before the end of 1931.

Plans, which were rapidly outlined for conversion of the four pulverized coal fired boilers to oil burning units, contemplated the following changes: removal of Lopulco burners and closing of burner openings in the arch, installation of combination coal and oil burners in the lower half of the front furnace walls, removal of lower portion of hot air downtakes and extension of air ducts to connect with wind boxes at the burners, replacements in forced draft apparatus, establishment of a new operating floor at burner level, and moving combustion control and instruments to this new level. Several objectionable features and many difficulties would have been encountered in the execution of this plan. It required rebuilding the front walls of three boilers and the removal of a portion of the new Bailey-block front wall on Boiler No. 34. The forced draft systems were inadequate, and, in the case of Boiler No. 36 equipped with the old type Ljungstrom heater unit, two booster fans would have to be included.

It was soon realized that a reconstruction program of such major proportions would seriously affect the economic advantages of low cost oil. It was decided, therefore, to carry out sufficient experimental work to determine whether or not it would be possible to fire these boilers with oil in a downward direction by inserting burners in the arches, without supplying the total air for combustion at the burners. Accordingly, the upper housing and fan tails of the Lopulco burners were removed, leaving in place the cast-iron thimbles which gave clear openings $8^1/_2$ in. × 22 in. through the arch. The primary air pipes were extended to these openings so that 18 to 24 per cent of the required air could be supplied through the primary air system.

The initial trial with mechanical atomizing burners was unsatisfactory because the quantity and pressure of the air available was inadequate. A portion of the cone spray impinged on the front wall and unburned oil was carried into the boiler tubes. Flames did not carry to the lower part of the furnace and satisfactory conditions were not obtained at any time regardless of rating. But the fact that it was possible to develop about 85 per cent of the desired capacity with this initial arrangement indicated successful possibilities. Flat-flame mechanical burners were tried, but the tips could not withstand the temperature conditions, and at higher capacities combustion was unsatisfactory. Subsequent experiments with steam atomizers demonstrated the feasibility of the firing of oil through the arches.

With definite assurance of success established, Boilers Nos. 35 and 36 were each equipped with eight steam atomizing burners. One burner was inserted in each coal burner opening with no provision for air supply at the burner other than primary air through the 5-in. pipe previously used for coal burners and tertiary air. This air was supplied at atmospheric pressure, induced by furnace draft through the $8^1/_2$ in. × 22 in. arch openings. This installation operated successfully for several months, but steam output fell short of capacity with pulverized coal.

As coal in storage had to be reduced, Boilers Nos. 33 and 34 were continued in operation with pulverized coal. This afforded an opportunity to work out an oil firing system for these two boilers which would meet the following requirements: (1) reduction in time and labor required to change burner systems from one fuel to the other; (2) elimination of noise produced by steam atomizers; (3) saving of steam required for atomization.

The first step was to provide higher pressures and greater volume of air at the burner. This was done by making changes in the forced draft system. The unsatisfactory conditions which were encountered in the initial trials with mechanical atomizers were therefore corrected and favorable conditions established for the installation of oil burners of that type.

The rear section of the upper housing of the Lopulco burners was cut away and remodeled to provide a free passage for tertiary air. A hole was cut in the front side of the fan-tail nozzle to receive the barrel of the oil burner which was inserted through the front of the upper housing. (See Fig. 5.) Tertiary air amounting to about 43 per cent of the total requirements was provided from the secondary air downtakes at the rear and conveyed to the front of the boiler through large ducts. Branch downtakes were erected to deliver air from the manifold in front of the boiler to the individual burner housings. A flared tip was added to the lower end of the fan tail to form a constriction in the air passage for the purpose of increasing the velocity of the tertiary air to the furnace. This air enters the housing with a static pressure of 0.1 in. or less, but the pressure within the housing is built up to 0.4 in. by conversion of velocity head. No change was made in the arrangement of the secondary air supply which is delivered by air cooling lanes in the side walls of the setting and discharged to the furnace through openings in the front wall. The volume of primary air was increased by installing rather large bypass ducts leading directly from the primary air header to the burners. Blast

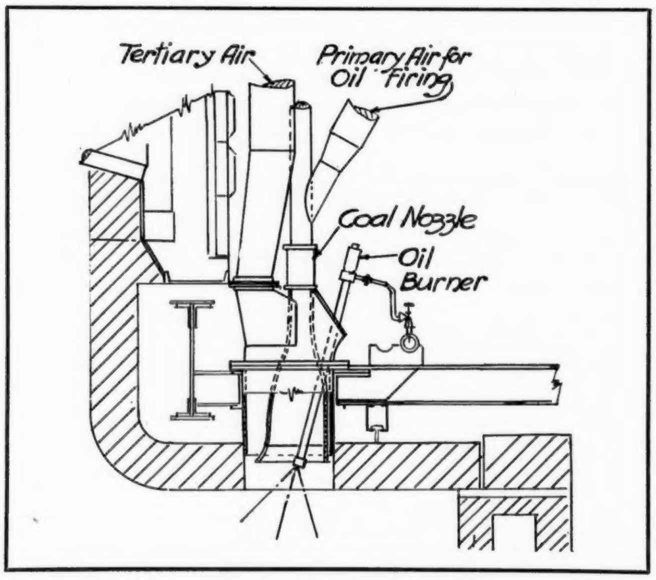

Fig. 5—Vertical coal and oil burners, Narragansett Electric Company, South Street Station.

gates were installed in the air piping to the feeders to prevent leakage and the passage of heated air through the feeders when burning oil.

Boilers Nos. 33 and 34, equipped in the manner described, were operated under observation for several months with satisfactory results in performance and capacity. The success obtained with the mechanical atomizing system and the improvements in operating conditions warranted the replacement of the steam atomizers in Boilers Nos. 35 and 36. This work was completed early this year so that all four boilers are now equipped with the combination arrangement which permits the firing of either pulverized coal or oil.

Various types of deflectors intended to give the entering air turbulence or a whirling motion before meeting the spray were tried with each type of burner, but the results were not satisfactory and no baffles or deflectors are used.

To correct a reduction in superheat with oil firing, a baffle was installed in each boiler, blocking the space between the rear tube headers and the bend in the hair-pin superheater and thus forcing all of the gases through the superheater. This alteration raised the superheat in three of the boilers to within 20 fahr. of the temperature obtained with coal firing at normal steaming rates. It had no effect on Boiler No. 34, the furnace of which is equipped with Bailey blocks. Superheat in this case averages about 50 fahr. below the temperature produced by combustion with coal.

Although the steam atomizers are no longer in use it may be of interest to mention a few of the operating characteristics of both types for the purpose of comparison. The mechanical burner has an apparent advantage when exposed to intense radiant heat as the area of the exposed tip is smaller than that of the steam atomizing unit. To this fact may be attributed the longer life of the mechanical burner tip under the particular conditions encountered on this job.

The steam atomizer produces a flame of intense brightness as a result of efficient atomization and turbulent mixing action with the enveloping air. Combustion is completed within a relatively short distance from the burner. The upper part of the furnace is relatively clear at normal rates and good furnace conditions may be obtained at steaming rates up to about 180,000 lb. per hr. On the other hand, the mechanical atomizers produce longer and softer flames which, at high ratings, utilize almost the entire furnace.

Gas analysis at the same steaming rates reveals CO_2 between 13 and $14^1/_2$ per cent with mechanical atomizers and 12.9 to 13.5 per cent with steam atomizers (with coal $13^1/_2$ to 15 per cent).

No evaporation tests have been conducted but the efficiencies of the two types, neglecting the atomizing steam of around 2.4 per cent, are apparently nearly equal and differ but slightly from efficiencies obtained with coal. The continuous steaming rate with steam atomizers is less than with pulverized coal, while with mechanical atomizers it is practically the same, the limitation being moisture carry-over with the existing type of steam drum baffle.

Cylindrical Type Coal Burners Fitted with Oil Firing Units at the Kneeland Street Station, The Edison Electric Illuminating Company of Boston

The Kneeland Street Boiler Plant supplies steam to a high pressure district heating system in downtown Boston. For this service, 3 Stirling boilers have been installed which normally operate at 210 lb. pressure. When fired with pulverized coal, two of these units each have a capacity of 250,000 lb. per hr., and one of 350,000 lb. per hr. Furnaces are of the hopper bottom type with water-cooled side and front walls. Four Riley Stoker Company flare-type turbulent burners are installed in two rows in a refractory burner wall under the mud drum of each boiler.

A study of conditions indicated that if oil firing units could be provided without interference with the operation of the pulverized coal combustion system, a saving in fuel costs could be realized at the prevailing cost of fuel oil.

Practically all of the space under the boiler plant was occupied by water storage tanks but available accommodation permitted the installation of a 24,000-gal. tank which is used as a service tank and at the same time provides sufficient storage for truck or railroad car delivery.

The Riley coal burners consist of sheet metal housings with 30-in. dia. (36-in. for 350,000 lb. boiler) openings toward the furnace, around which are arranged the guide vanes to give a spin to the secondary air as it enters the furnace. The coal and primary air enter through a centrally located 10-in. (some 12-in., others 14-in.) tube connected to a volute inlet head equipped with a tangential inlet to which the pipe from the pulverizers is attached. A bolted cover plate with a central

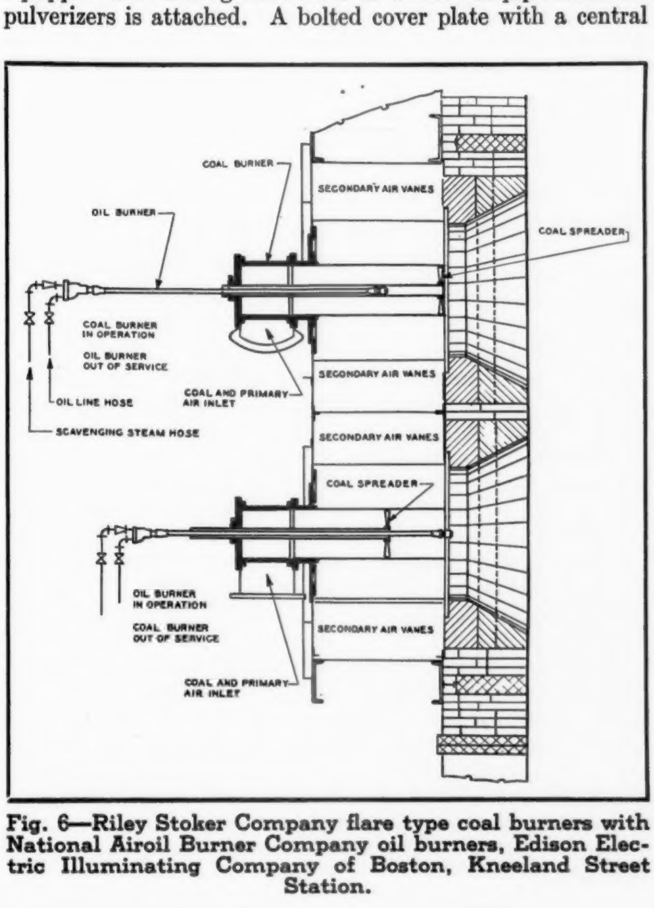

Fig. 6—Riley Stoker Company flare type coal burners with National Airoil Burner Company oil burners, Edison Electric Illuminating Company of Boston, Kneeland Street Station.

bushing on the outside end of the burner head, together with a 3-in. spreader sleeve through the central axis of the burner unit completes the assembly. The spreaders are fastened to the end of these sleeves and the sleeves are supported by cover plate bushings. A sliding fit permits the adjustment of the spreader to the proper operating distance from the end of the 10-in. central coal tube.

From examination of the coal burner construction it was seen that the spreader sleeve formed a suitable opening and bearing for the insertion of oil burners. The only expense involved was to change the spreader sleeves from 2 in. to 3 in. on the 250,000 lb. boilers. (See Fig. 6.) No changes were made in the design of the furnace, draft systems, or in any of the boiler auxiliary equipment.

Mechanical atomizing burners were developed by the National Airoil Burner Company for installation through the spreader sleeves. These oil burners develop slightly over 50 per cent of the steam generating capacity of the coal burners.

Under normal conditions, oil is fired to the full extent of the installed oil pumping and heating capacity, with coal in reserve. As the load increases coal is used as required, through the same burners that are burning fuel oil. Due to the low load factor of the district heating system, it is possible to generate approximately 90 per cent of the steam with fuel oil during the winter months, and an even larger percentage during the summer months. Oil accounted for 90 per cent of the total fuel requirements during the month of December 1932.

The water-cooled furnaces are of the Bailey block type, and it is desirable to maintain some slag on these blocks in order to maintain a proper furnace temperature. The firing of a small amount of coal is adequate for this purpose. Owing to the fact that the boilers cannot be operated at full load when fired with oil, no performance comparison with coal at such load is possible.

However, satisfactory results are obtained with oil at the lower ratings and with combination oil and coal burning at the higher steaming capacities. When the boilers are operating at a load greater than 60 per cent of maximum, oil is used as the base fuel and is fed to the furnace at a constant rate while the combustion control equipment regulates the quantity of coal burned and automatically maintains a constant station header pressure.

General Comments and Conclusions

It is evident, from a review of the methods employed in the conversion of combustion systems from coal to oil in the few plants included in this paper and of others not included, that furnaces of water-wall or refractory construction, designed for pulverized coal burning, are adaptable for oil firing with minor changes. Indeed in most cases no changes whatever are required. It has also been demonstrated that practically all types of pulverized coal burners can be revamped at small expense and can be fitted with oil firing units. Also, results indicate that performance with oil in these converted installations is fully equal to that obtained with the original coal burning system.

However, it should not be assumed that revamped burners are equal in performance to the modern combination burners of proper design now available. Probably, in some cases, improvement in burner and combustion efficiency could have been realized with entirely new combination equipment. With the unprecedented low price of oil, however, this improvement and the possible betterment in operating facilities could hardly warrant the relatively high investment required for new combination equipment with consequent changes in furnace and air system construction and the retirement of existing coal burners.

The experience of the plants under consideration show that, as long as the viscosity of the oil is maintained at the proper value and the capacities of units are limited to well within the range set by the manufacturer of spray plates or tips, no troubles are encountered in obtaining satisfactory mixing of

air and fuel with coal burners when equipped and operated with oil firing units.

In general, the air delivered by the cylindrical coal burner is discharged with a rotary motion and with this type, air diffusers or spreaders are used for operation with oil burning. The diffusers add appreciably to the efficient mixing of fuel and air and tend to shorten the flame. On the other hand, fan-tail or intertube coal burners, when equipped for oil firing, are now in operation without diffusers with satisfactory results.

The development of vertical firing of oil through furnace arches in a downward direction at the South Street Station of the Narragansett Electric Lighting Company came about, during the past year, in an effort to reduce operating costs at the earliest possible date by the use of low cost fuel oil.

Plans first considered contemplated the installation of the conventional horizontal type combination burners. This plan was rejected because the cost would have been excessive and also on account of the extended interruption in steaming capacity which would have been necessary with a reconstruction job of such large proportions. The use of steam atomizing burners through the openings in arches made available by the removal of vertical coal burners in two boilers served as a quick solution to the problem. Subsequently the Lopulco coal burners were replaced after having been remodeled to permit the installation of mechanical atomizing burners. The dual arrangement which is installed in four boilers permits the firing of either coal or oil.

In the Montaup Electric Company's Somerset Station excellent results had been obtained with vertical coal firing. In fact, a comparison of combustion performance with three vertically and two horizontally fired boilers, with substantially the same furnace arrangement indicated a preponderance of favorable results with vertical firing. Apart from the kind of fuel used, the outline and proportions of the Somerset Station furnaces, which are high and wide but relatively narrow and the relationship thereto of the inclined front tube bank of the Stirling boilers and of the water screen, composed a combination of physical conditions particularly suitable to the combustion requirements and flame shape developed by vertical firing. Furthermore, the zone of high temperature in the furnace with downward firing is concentrated in a screen of flame opposite the tube bank and results in an increase in the absorption of radiant heat by the boiler compared to that obtainable with a horizontal flame in the lower section of the furnace. With the zone of high temperature located in the upper two-thirds of the furnace, the load bearing properties of the refractory in the lower section of the walls should be improved on account of the exposure at lower temperatures.

With these favorable considerations and the need of facilities for combination firing of oil and coal during any operating period, it was decided to make the necessary changes in the vertical coal burners as previously described.

It should be noted that, with the Montaup design, two oil guns are in service in each coal burner while only one is used in the South Street Station with the same type and make of coal burner. The density of the oil spray with the double unit is less and the contacting surface is larger, but performance and burner action are apparently satisfactory with both arrangements.

In the Somerset and Burlington stations, excessive plugging of preheaters has been encountered with oil firing. Plugging and corrosion of preheaters will occur in any plant with gas outlet temperatures in the range of 325 to 350 fahr. and using fuel oil having a sulphur and hydrogen content in excess of 2 per cent and 11 per cent, respectively. Contributory causes of these troubles are: improper distribution of gases in the air and gas passages resulting in temperatures considerably below the mean operating temperature in various parts of the preheater; formation of ferric sulphate scale in tubes or passages located in the cool regions; and large quantities of unburned products carried to the preheater when starting a boiler after a shut down, in combination with condensation of vapors during the initial firing period. A satisfactory solution of these problems remains to be worked out. Pending a solution, plugging and corrosion will continue because a large part of the oil used for steam generation is high in sulphur and hydrogen content. (Trouble of this character with coal firing is of minor extent because the ash, carried by the gases through the draft system, serves as a scouring agency.)

Decrease in superheat temperature takes place in almost all cases of conversion of pulverized coal furnaces to oil firing. To a large extent, this is due to the lower percentage of excess air required for oil burning. This deficiency can usually be remedied by minor changes in the first pass baffle. However, with combustion systems using both oil and coal, it may be necessary to operate at a lower total steam temperature when using oil, as changes in baffles may result in excessive temperatures when coal is burned.

Power Show at Chicago to Be at the Stevens Hotel

The 6th Mid-West Engineering and Power Exposition at Chicago, previously scheduled for the Coliseum, will be transferred to the Exhibition Hall of the Stevens Hotel, the center of "Engineering Week" activities of the Century of Progress.

This change in location will permit the engineering profession visiting Chicago to visit the Show while attending their meetings, and brings together the week's big "Engineers' Day" banquet and the Exhibit in the same building.

Approval of participating in "Engineering Week" of the World's Fair has been given already by 19 engineering associations. Others will also participate.

No engineer can afford to miss the opportunities of "Engineering Week." The arrangements as a whole have progressed sufficiently to indicate that the conventions and exhibit will be in the nature of a vast school showing what is new and advanced in thought and machinery.

The Program for the World Economic Conference

The World Peace Foundation has recently published a very interesting book entitled "The Program for the World Economic Conference. The Experts' Agenda and Other Documents with an Introduction by James W. Angell."

In his introduction to the Draft Annotated Agenda prepared by the League of Nations Commission of Experts, James W. Angell, Professor of Economics at Columbia University, clearly defines the fundamental economic problems with which the Conference must deal, and points out their close relationship with the problems of war debts, disarmament and peace.

The summary introduction gives a detailed yet well-rounded picture of the problems which beset us and the possibilities of solving them through international cooperative action.

This small volume should prove of invaluable aid in understanding the significance of the Draft Agenda which provides "clear evidence that the real interests of the participating countries, often widely divergent at first glance, are fundamentally almost identical."

Copies of this book can be obtained from the World Peace Foundation, 40 Mount Vernon Street, Boston, Mass. Price: $1.00, cloth bound and indexed; 50 cents in paper, unindexed.

The Principles of Underfeed Combustion and the Effect of Preheated Air on Overfeed and Underfeed Fuel Beds[1]

By P. NICHOLLS[2] and M. G. EILERS[3]

This paper is based on investigations conducted at the Pittsburgh Experiment Station of the U. S. Bureau of Mines. It shows that in underfeed burning the factor of rate of ignition is much more important than it is in overfeed fuel beds and that it fixes limits to the outputs that can be obtained. It uses the principles determined from the experimental results to interpret the much more complex action in fuel beds of commercial underfeed stokers. It also shows what effect preheated air has on overfeed and underfeed fuel beds and how this preheat is utilized. The results from burning a number of fuels on the underfeed principle, both without and with preheat are given. The variables investigated were kind and size of fuel, and rate and temperature of the air supplied.

THE purpose of this paper is to present the results of an investigation conducted at the Pittsburgh Experiment Station of the U. S. Bureau of Mines. It is one of a series of studies which have been made by the bureau on the burning of solid fuels to obtain measures of the actions which occur in fuel beds in the burning of fuel and the clinkering of its ash. When this investigation was started it was intended to restrict it to a study of the effect of preheat; however, as preheated air is more commonly used with underfeed stokers it became necessary to include underfeed burning in the investigation and this was the major feature of the investigation.

Because the two types of tests were interlocked, it is not convenient to separate them entirely in this report; the study on the effect of preheat on overfeed fuel beds will be treated first, and the effect of preheat on underfeed fuel beds will be included with the report on underfeed combustion.

Effect of Preheat on Overfeed Fuel Beds

The objects of the investigations were restricted to studies of the effect of preheated air on the combustion in the fuel bed, and did not include the economy or desirability of preheat or even its effect on combustion above the fuel bed, except as far as the latter can be deduced from the composition and temperature of the gases leaving the fuel bed without and with the use of preheated air.

Although there have been numerous papers and reports on the effect of preheat on the overall operation of furnaces and on economy, no record was found of any detailed studies of its effect on combustion. Reports have referred to the increased clinker formation caused by preheat, and the limiting of preheat temperature because of clinker troubles or increase in the cost of upkeep of the stoker parts, but it can be understood that there would be little opportunity to measure the effect of preheat on combustion in the fuel bed.

The over-all effect of the preheat on a fuel bed is given by the change in the composition and temperature of the gases leaving the bed. It can be predicted that the rate of reaction in the bed will be increased and that, as a consequence, the rate of burning will be increased for the same rate of air supply. If a fuel bed is deep enough, the endothermic reaction of the conversion of CO_2 to CO occurs. If the formation of CO is increased by the preheat, then some of the sensible heat of the preheated air will be absorbed, and the increase in temperature of the gases leaving the fuel bed will be less than that which would be computed from the preheat added; of course, even supposing there were no increase in CO, the increase in temperature of the hot gases would be less than that of the preheat because of the increase in the specific heat of gases with temperature.

A further cause for the loss of some of the preheat will exist if the clinkers or ashes leave the system at a higher temperature than they would without preheat.

It was evident that the differences in the quantities to be measured would be small, so that all auxiliary conditions of test would have to be identical, and measurements must be accurate. Even with the closest regulation it is very difficult to get two burnings to give exactly the same result, particularly with fuels which cake. Considerable experience had been obtained in the study of fuel beds in connection with the determination of the combustibilities of cokes (*1*);* also, coke forms the main part of the bed even when burning coal. It was therefore decided to follow the same method and, as a beginning, to use coke as a fuel since the principles involved could be more easily determined and better illustrated by a fuel free of volatile matter.

Apparatus Used. Fig. 1 shows the set-up used. The furnace was of welded construction with refractory lining. The inside was 20 in. dia. and 44 in. high from the grate bars. There were 26 half-inch pipe sampling holes at $1^1/_2$-in. intervals from the grate level, these being scattered round the circumference. The air was supplied by a fan capable of giving 9-in. pressure; the air passed through a measuring orifice and the quantity could be closely regulated. The preheater was built specially for these tests, and was designed to give up to 1000 fahr. preheat with the maximum estimated quantity of air. Two sizes of premix gas burners were used; the gas was burned in a combustion chamber with checker-brick to avoid flame

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* Numbers in parentheses refer to references at end of article.

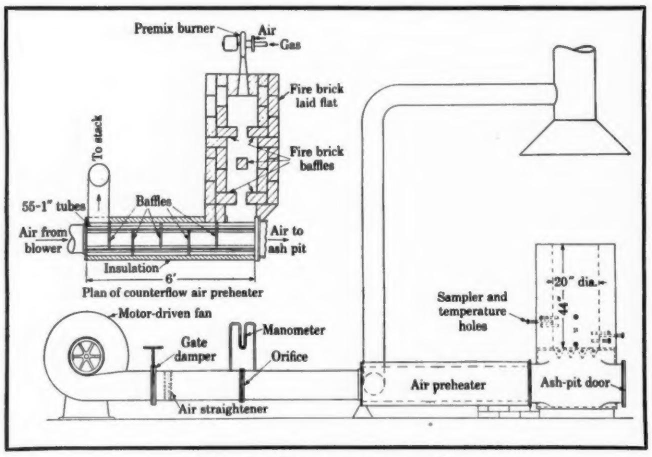

Fig. 1—Apparatus used.

impingement on the preheater tubes. The temperature of the hot gases was controlled by the addition of air so that it would be the minimum above the preheat temperature. The air leaving the preheater passed through a mixer before entering the ashpit. Its temperature was measured by a shielded thermocouple at a position of high velocity.

The Bureau's standard water-cooled gas samplers were used for inserting into the bed through the various sampling holes. Fuel-bed temperatures were taken by optical pyrometer. All gas samples and temperature observations were taken at 1 in. distance from the vertical axis of the furnace. Other instruments and measurements were of standard type.

Test Procedure. Because the procedure was essentially the same as that used in the combustibility tests referred to, it will not be described in detail. A very rigid specification was followed to insure duplication of conditions. It consisted in building up a fuel bed to a 24-in. depth, allowing it to come to equilibrium of burning, and then maintaining it at that depth during the period when measurements were taken.

Three complete sets of gas samples and other measurements were taken during one test and the bed was frequently restored to its standard condition at fixed times. The samples were taken one at a time starting at the top of the bed so that the portion below the sampling position was not disturbed previous to the taking of the sample.

The coke used was made by the Philadelphia Coke Company in Koppers ovens using a mixture of 80 per cent Powellton seam coal and 20 per cent Pocahontas coal. It was crushed and carefully screened to 1 to $1^1/_2$ in. square mesh. Its analyses and properties were:

Proximate Analysis, per cent:	
Moisture	0.6
Volatile matter	0.7
Fixed carbon	91.3
Ash	7.4
Ultimate Analysis, per cent:	
Hydrogen	0.5
Carbon	89.5
Nitrogen	0.9
Oxygen	1.0
Sulphur	0.7
Ash	7.4
Softening Temperature, fahr	2730
Weight per cu. ft. of $1\text{–}1^1/_2$ in. size, pounds	31.8

Results of Tests. Four air temperatures were used, 80 (normal), 400, 600 and 800 fahr. Fig. 2 shows the values of the CO_2, CO, O_2 and N_2 in per cent by volume against the height of the fuel bed, and also the temperatures by optical pyrometer. Each point is the average of the nine sets of readings. A few gas-analysis values were rejected because they showed internal evidence of errors in the sampling or the analysis. The water vapor is not plotted; from the analysis of the coke its value would be 0.7 per cent by volume. It is also possible that some producer action of the water vapor in the air and from the coke had occurred; it was not considered worth while to include the extra precision and labor necessary to check these factors. The portions of the curves in the first $1^1/_2$ in. of the bed below the first sampling position are drawn arbitrarily. The largest variations between individual observations occurred with the first two sampling positions because these are most affected by pieces of clinker, although the attempt was made to remove the clinker each time the bed was brought back to standard.

The figure shows that the preheat caused larger differences in the reaction in the lower part of the bed, and that it increased the rate of reaction.

The temperature observations were, as usual, the weakest part of the measurements. Of course, they are the temperature of the coke surface, and the optical pyrometer will show large variations over the small area which is seen through one hole; several readings were taken at each observation, and the results averaged. The dip in the temperature curves at 12-in. height shows a drop in temperature which should not occur and is due to conduction to the walls or to convection of cooler gases from the walls.

The figure shows that the preheat is used partly in increasing the CO reaction and partly in raising the temperature. Comparing the values for 80 and 600 fahr. at the 15-in. height, computations show that about 45 per cent of the preheat was used in the conversion of CO_2 to CO and 55 per cent in increasing the sensible heat. The curves of Fig. 2 are based on the test points; computations show that from the heat balances the 600 fahr. curves should be closer to the 400 fahr. curves.

Fig. 3 shows the total carbon and hydrogen content of the gases per pound of air; the rate of burning is proportional to the carbon content; the dotted line will be referred to later.

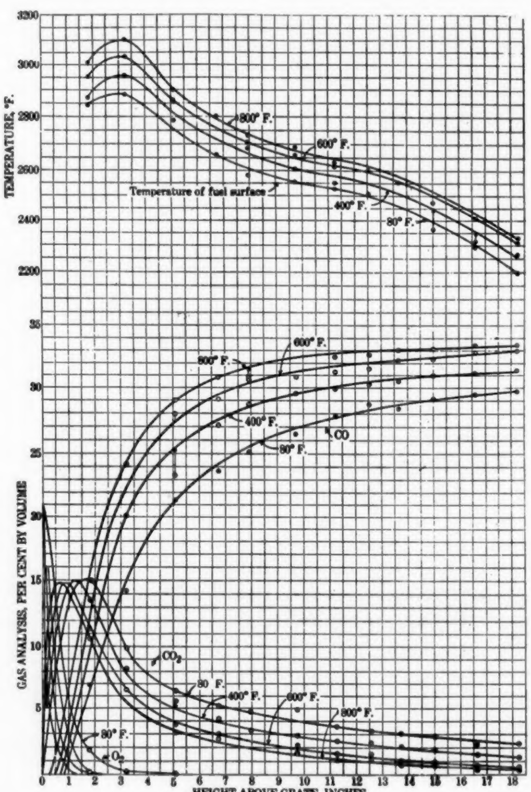

Fig. 2—Effect of preheat on the gas analyses and fuel bed temperatures of an overfeed fuel bed of high temperature coke.

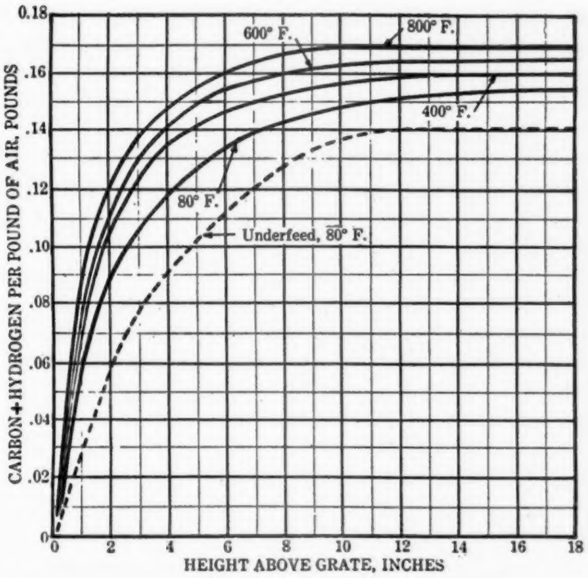

Fig. 3—Overfeed burning, high temperature coke. Effect of preheat on total combustible in gases.

The results illustrate the principles of the effect of preheated air in a thick fuel bed. One could deduce the order of the effect on a 10-in. deep fuel bed, for example, by taking the values at the 10-in. height. The actual values by gas analysis and by temperatures would be somewhat lower, however, because of the loss of heat by radiation from the top of the bed and by the quantity of heat required to raise the temperature of the incoming coke, assuming that it is fed in continuously at a rate equal to the rate of burning.

The values given in Figs. 2 and 3 are based on samples and temperatures taken at the center of the bed and therefore depict the actions in a uniform bed free from holes or cracks, or the effect of side walls. In service these factors are always present and reduce the average combustible in the gases below that which would be predicted for a given depth from Fig. 3; also, ash and clinker would always be present in service and would increase the apparent depth. One can, however, use Fig. 2 to predict with fair accuracy the relative rate of burning that will result from the maintenance of various depths of fuel bed.

Further Work with Preheat. The investigation could have been extended to obtain actual values with normal depths of fuel beds; there would be no object in doing this for cokes, but it could have been done for coals. Preheat is but little used with the overfeed type of fuel bed. Such tests with caking coals would necessitate introducing the factor of breaking up the fuel bed, and this operation is difficult to standardize, so that the accuracy of results is affected. If such tests had been made it would probably have been of most practical value to have used fuels high in moisture. However, it was not considered worth while to extend this phase of the investigation, but rather to study the effect of preheat on the burning of bituminous coals on the underfeed principle.

Underfeed Burning

Previous Work. The principles of overfeed or hand-fired burning are well understood and there have been many investigations of them. The fundamental ones are those made at the Bureau of Mines by Mr. Kreisinger and his co-workers (*2*). Although other investigators have not studied the actions at different heights in the fuel bed, yet all tests of domestic and other small types of furnaces yield overall data on the principles of the burning of different fuels, but relatively rarely has the effect of secondary air, supplied purposely or by leakage, been eliminated. The investigation which the bureau has made on the burning of coke (*3*) extended the study of overfeed fuel beds to the effect of the size of free-burning fuels on characteristics of combustion. A similar investigation has been completed for anthracites.

No corresponding studies have been published of the principles of underfeed burning. There have been investigations of some details of the combustion with underfeed stokers, but these give little information on the action in the bed. Mr. Bert Houghton (*4*) removed a section of fuel from a retort and by analyses of various sections determined how far the fuel had been consumed. The composition of the gases arising from the fuel bed at various locations has been studied by others. The progress of combustion on a chain-grate stoker was rather ingeniously examined recently by J. D. Maughan (*5*), who fed in a wire screen with the coal and, when it completely covered the grate, quickly withdrew it and quenched the fuel. Analyses of various sections through the bed showed the distribution of the fixed carbon and volatile remaining.

Types of Fuel Beds. Although the term "underfeed fuel bed" is used in this report, yet the same principle of combustion occurs in beds to which that term would not apply. The term "up-burning" is sometimes used, but that also is not comprehensive enough. It is therefore worth while to review various types of fuel beds and to connect them with the principles they include. The discussion which follows may be considered somewhat elementary, but at least it insures clarity of thought.

The type of a fuel bed is fixed by the absolute direction of flow of the fuel and its flow relative to the air; both of these can be constrained to move in any direction desired. The ash will flow in the same direction as the fuel independent of gravity unless it becomes fluid, when gravity and the temperatures of the zones it flows into will influence its motion.

Fig. 4 shows six of the possible types. Type A, representing hand firing, is of the overfeed principle. Type B shows what we have termed the "unrestricted-ignition" underfeed principle. Type C evidently is the same as B in its combustion principles, but differs in the ash disposal; it is illustrated by the Hawley down-draft heating boiler. Type D, as representing a traveling-grate stoker, is of interest; the length U of the fuel bed is burning on the pure underfeed principle; the length O is burning on the overfeed principle; and some unknown length P is in what we have termed the change-over state—that is, the burning is adjusting itself because of the cessation of the ignition action. Type E, as represented by the burning in a Molby heating boiler, has some of the underfeed principle at the upper part. Type F represents the pot type stoker; the burning will be of the underfeed type with restricted ignition.

Pure Underfeed Burning. The term "unrestricted-ignition underfeed" burning used above implies that with a fixed rate of air supply there is no imposed restriction which limits the rate at which fresh fuel may be ignited; thus in Type B of Fig. 4 the fuel is free to ignite and the level of the line of ignition will rise or fall as the rate at which the coal is pushed in is greater or less than the rate of ignition. In Type D there is no imposed

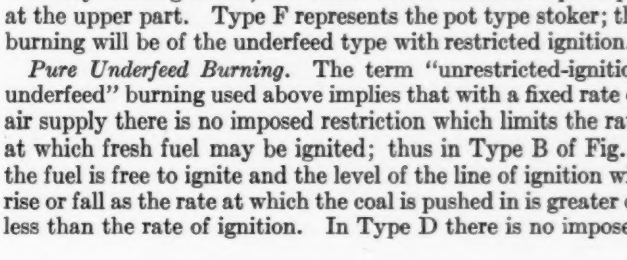

Fig. 4—Diagrammatic representation of six types of fuel beds.

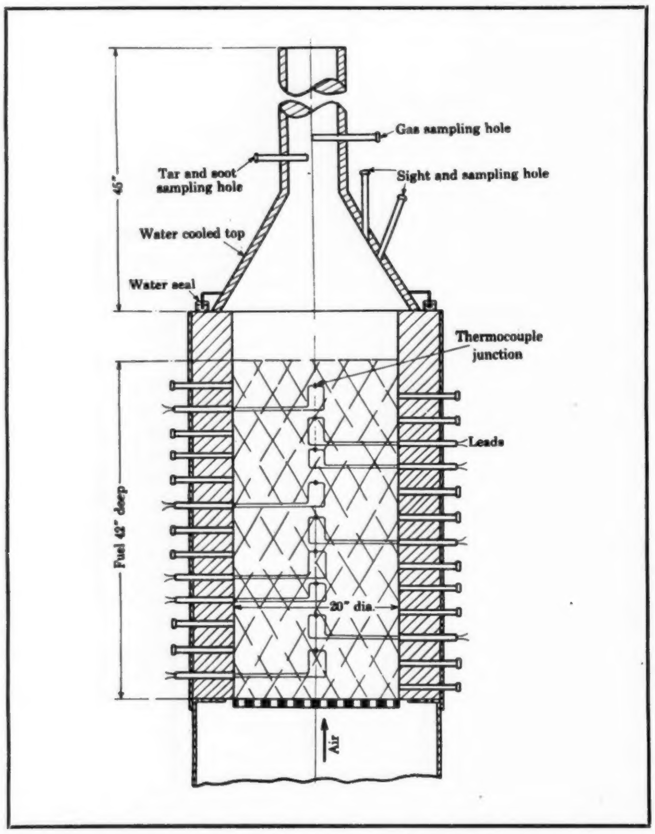

Fig. 5—Diagram of fuel bed for underfeed burning tests.

condition limiting the rate at which the fuel in the length *U* can ignite, and unrestricted-ignition underfeed burning results, but as soon as the line of ignition reaches the grate bars, the type of combustion changes.

The rate of ignition in Type F is controlled, and it can only conform to the definition of unrestricted-ignition underfeed burning when the rate of coal feed is equal to or greater than the rate of ignition; in addition, the burning is not completed in the pot. The same arguments would apply presumedly to all larger underfeed stokers, with the addition that the motion of the fuel may be much more complex.

Equilibrium Fuel Beds. The term "equilibrium fuel bed" is used in connection with the experimental work and requires a definition although the term is self-explanatory. It is used to define a fuel bed which, for a constant rate of primary air, maintains the same character of combustion and thickness.

In the overfeed, Type A, the bed will be in equilibrium when such a thickness is reached that the rate of burning is equal to the rate of fuel feed. In the underfeed, Type B, the bed is in equilibrium when such a thickness is reached that the rate of burning is equal to the rate of ignition; if the rate of fuel feed in Type A, or the rate of ignition in Type B is greater than the rate of burning, then the thickness of both the beds will increase indefinitely.

Method of Test. Evidently it was desirable to attempt to determine some of the fundamental principles of underfeed burning—that is, to study a fuel bed as represented by Type B of Fig. 4. The use of a bed such as Type F would correspond more nearly to practice, but it would be difficult, if not impossible to separate the fuel characteristics from the conditions imposed by the particular design of pot used. It was preferable to have a furnace such as *B* in which both the fuel and air would be fed from the bottom, and a number of schemes were considered. One of the requirements was that the fuel should be fed uniformly over the area of the bed, which would be difficult to insure without considerable expense of construction. Finally, the same method was adopted as was used in a previous investigation on clinkering (*6*).

The method consisted in starting with a deep bed of fuel and igniting it at the top. This gives a true underfeed burning and restricts the factors affecting the combustion to the fuel and the rate of air supply; for fundamental studies it has the further advantage that the fuel is stationary. It has the disadvantage, compared with forcing the coal in and keeping the burning zone at one position, that the cooling effect of the refractories is greater.

Successful operation when burning caking coals in underfeed stokers is dependent on the breaking up of the caked or coked fuel. This is a necessity in practice, yet it introduces a variable that is difficult to control. Although it was recognized that the caking would seriously affect the burning, it was nevertheless thought advisable to make the first series of tests without disturbing the fuel bed in any way; so doing gave truer measures of the fuel characteristics. Knowing these characteristics, the breaking-up factor could be superimposed in other tests.

Apparatus. The set-up was essentially the same as shown in Fig. 1 except that a water-cooled cone with chimney was used as a top cover to collect the gases so that average samples could be obtained; this cover had a water seal for prevention of in-leakage and for ease of removal.

Fuel Bed and Observations. Fig. 5 shows how the fuel bed was arranged. The diameter of the pot was 20 in. and the depth of the fuel 42 in. All fuels were carefully screened to definite size limits and the furnace was loaded by small increments. Nine thermocouples of No. 28 B. & S. chromel-alumel bare wire were laid in as shown; the junctions were on the center line and were placed in a 1-in. length of small porcelain tubing. The exact height of each junction was recorded by measuring from a crossbar over the top of the furnace. The wires from the junction were run down so that the heat would strike the junction first. The couple leads went to a cold junction and thence to a switching arrangement by which each could be connected to a portable potentiometer, or one or more connected to a recording potentiometer; usually only one at a time was connected to the recorder.

The fuel was ignited by means of a fixed weight of small-sized charcoal and petroleum coke, wetted with kerosene, which was spread over the top of the fuel. The cover was not put on until it was seen that there was even ignition all over the area.

The air rate was maintained constant at a fixed weight of dry air, the pressure drop through the orifice being changed during the test for any material change in the air temperature or barometric pressure. Gas sampling was started after the cover was put on; the samples were taken continuously over 10 to 20-min. periods, depending on the rate of burning.

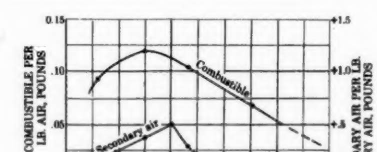

Fig. 6—Underfeed burning, high temperature coke.

The top couple was connected to the recorder first. When the ignition line reached the couple its temperature would begin to rise and the record obtained gave a good measure of the progress of the ignition. When the temperature reached 30 mv. (1340 fahr.) the couple was switched to the portable potentiometer and the next lower couple was connected to the recorder.

The progress of combustion was also recorded by observations through the 26 sampling holes in the furnace, and the time when the top of the bed or the ignition reached each hole could be very closely fixed.

No samples were taken or temperatures measured in the bed itself during the regular tests, except that some special observations were made of the top of the bed through the sampling holes in the cone cover.

The tests with preheat were conducted in the same manner except for the preliminary period of bringing the whole of the fuel bed up to the temperature to be used. During this period the couple giving the temperature of the entering air and the couples placed at mid-height and at the top of the bed were put on the recorder to assist in avoiding excess heating of any part of the fuel.

The test was continued until the fuel was consumed, except for some tests of bituminous coals in which the caking caused very uneven burning. The furnace was allowed to cool and then the residue was examined and measures taken of the ash, clinker and their combustible content.

Data Obtained. All the main data were plotted against time as abscissa. Against height above the grate as ordinate were plotted the 30 mv. position of the thermocouples in the bed and the level of ignition by observation; the slope of these lines gave the rate of ignition in inches per hour, and from the known weight per cubic foot of the fuel as placed in the furnace the rate of ignition in pounds per square foot per hour could be computed. The plot of the observed level of the top of the fuel bed on the same diagram gave the thickness of the ignited portion at any time.

The flue-gas analyses were also plotted against time; from

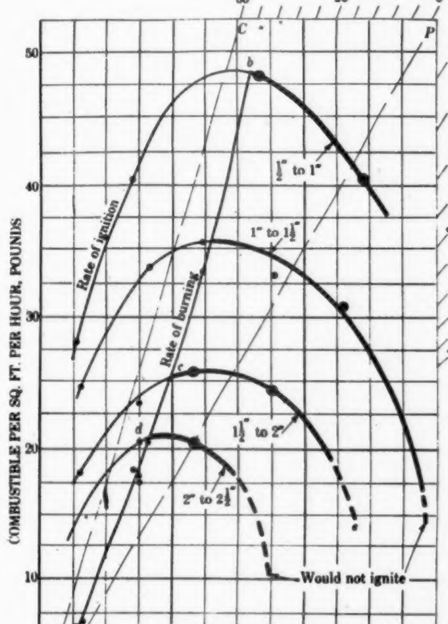

Fig. 7—Underfeed burning, high temperature coke; rate of ignition and rate of burning with rate of primary air and size of coke as variables.

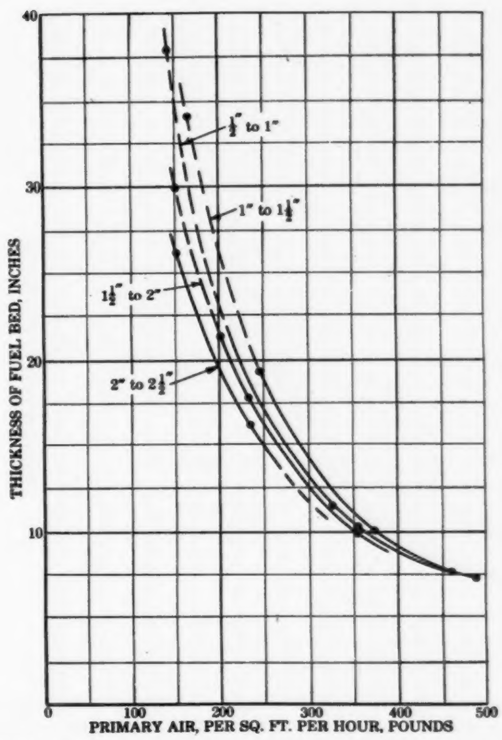

Fig. 8—Underfeed burning, high temperature coke; thickness of fuel beds, with rate of primary air and size of coke as variables; see Fig. 7.

these and the known rate of air supply, the rate of burning was plotted. The integral of the rate of burning gave a computed value of fuel burned which was checked against the known weight of fuel fired, corrected for combustible in the residue and the fuel used for igniting the bed.

Underfeed Burning of High-Temperature Coke. Coke is not burned in underfeed stokers, although it is reported to have been tried in small domestic pot-type stokers; also it has been burned on chain grates, and, as shown in Fig. 4, underfeed burning occurs in a portion of the bed. In spite of this lack of application in service, high-temperature coke was used for the first, and also the most complete, set of tests of underfeed burning. Coke is the most convenient fuel to use when investigating principles of burning, both because it eliminates the uncertainty of size of pieces that is present when one has to break up a caked or coked fuel, because the bed does not have to be disturbed by poking, and because the cost of the tests is very much reduced in that the gas analyses can be made in a much shorter time and in a water Orsat.

The primary factors to be investigated were: (1) Rate of air supply; (2) size of coke pieces; (3) temperature of primary air—that is, preheat. A series of tests was therefore planned that would give enough data to permit of fairly complete plots being made; the first were made with normal air temperature.

The high-temperature coke used in these tests was made from No. 8 Pittsburgh seam by the Lowell Gas Light Company in horizontal-through retorts; its properties have previously been reported. (7) Those of interest are:

Ultimate Analysis, per cent:	
Hydrogen	0.6
Carbon	88.8
Nitrogen	1.1
Oxygen	0.6
Sulphur	0.6
Ash	8.3
Ash softening temperature, fahr	2730
Weight per cu. ft. of the 1–1 1/2 in. size, pounds	26.8
Pounds of fuel per pound of combustible, ratio	1.12

The rates of combustion will be expressed in terms of the available combustible in the fuel, as this eliminates the variations in the non-combustible.

Variables of Rate of Primary Air and Size of Coke Pieces. The sizes of coke adopted as standard were those between the square mesh screen sizes of $^1/_2$ to 1, 1 to $1^1/_2$, $1^1/_2$ to 2, 2 to $2^1/_2$, all in inches. The air rates were kept constant during each test.

To understand the meaning of the results it is better to consider first those for one size of coke. Fig. 6 shows plots of the data for the $1^1/_2$–2 in. sized coke. It will require a detailed explanation and some study to interpret their meaning; because the same method of presenting data is used for other results they will be discussed at some length.

The abscissa is pounds of dry air per hour per square foot of grate surface. The left-hand ordinate scale is pounds of combustible (carbon + hydrogen) per hour per square foot of grate surface. The test points are shown and the curves beyond the range of the points are dotted. The two main plots are the rate of ignition and the rate of burning of combustible. The light-line part—*cb*—of the ignition curve means that it is for ignition only; the heavy-line part—*bd*—means that it is part of both the ignition and the rate of burning curves. The rate of burning curve is thus *abd*.

Considering these two curves, they show that at 100-lb. air rate the rate of ignition is about 21.5 lb. per sq. ft. per hr. but that the rate of burning is only 12 lb.; therefore the coke at the bottom of the burning zone is being ignited at a faster rate than the coke above it is burning (being gasified); consequently the thickness of the burning zone is increasing continually. At an air rate of about 200 lb. the rate of burning is the same as the rate of ignition, so that the live fuel bed will maintain a constant thickness. At air rates greater than 200 lb., the rate of burning could increase along a continuation of the line *ab*, but it cannot be greater than the rate at which the fuel is ignited, and consequently it does the best it can and follows the rate of ignition curve *bd* which, for this fuel, increases a little at first, reaches a maximum at 250 lb. of air, and then decreases with further increase of rate of air supply.

The ignition curve indicates that at high air rates the rate of ignition tends to approach zero; results given later will show that this occurred in some tests and it was impossible to maintain burning. Such occurrences are a common experience and are usually spoken of as blowing the fire out. This falling off of the ignition curve was, as might be expected, more in evidence with the high-temperature coke than any one of the other fuels tested. The causes for this action are two: first the fuel is ignited by the heat radiated from the hot fuel above; very

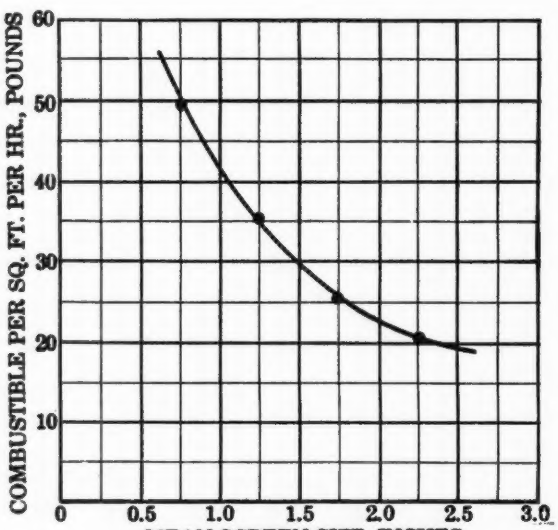

Fig. 9—Underfeed burning, high temperature coke; rate of ignition against size of coke.

little of the heating of the fresh fuel will be by conduction; at the same time the surfaces of the fuel are being cooled by the air passing over them, and this will tend to counteract the heating by radiation and, after some unknown rate which will vary with the fuel and its size, the counteracting effect will increase more rapidly than the increase in the radiation due to a higher rate of combustion. The second cause is that the fuel bed gets thinner as the air rate increases; after some undefined thickness is reached the temperatures through the bed will decrease and consequently the radiation will be less.

One curve in Fig. 6 shows the observed thickness of the live fuel bed. This thickness includes the clinker and unfused ash; the values given for this, and other curves which follow, were selected in the same manner from the plots of the observed values during the whole test. The full line part of the curve covers the range in which the thickness is constant; one would expect that the observed thickness would increase with time because of the accumulation of clinker, but the increase was usually small compared with variation caused by the method of observation. For these equilibrium beds of constant thickness, a mean value was selected.

The dotted part of the curve covers the range in which the thickness is increasing; the height of the bed when the ignition plane reached the grates is used for the thickness in this range.

The two upper curves of Fig. 6 show the pounds of combustible in the flue gas per pound of air supplied, and the pounds of secondary air required for perfect combustion per pound of primary air. The secondary air curve shows that secondary air would be required up to a primary air rate of 280 lb.

The foregoing results and the interpretations of them relate to the condition of unrestricted ignition. Commercial underfeed stokers have restricted ignition in the sense that the rate at which the stream of fresh fuel passes into the primary-air stream can be controlled. It is worth while at this stage to consider how the data of Fig. 6 can be applied to restricted burning. The following deductions refer to continuous operation with ability to restrict the rate of feed of the fuel.

(1) To obtain the maximum rate of burning possible with each rate of air supply, the rate of feed must follow the curve *abd;* no manipulation other than changing the area of the plane of ignition can make the rate of burning continuously exceed the values fixed by this curve.

(2) The maximum rate of burning possible with this coke and this particular size is about 26 lb. of combustible (or 29 lb. of coke) per sq. ft. per hr., and no manipulation can increase it.

(3) The equilibrium thickness of the live fuel bed for rates of air supply above 200 lb. and for the corresponding rate of fuel feed fixed by the line *bd* will be those shown by the thickness curve of Fig. 6. The equilibrium thickness for air rates below 200 lb. and for the corresponding rates of fuel feed fixed by the line *ba* cannot be predicted from these tests; they will not be as large as the values indicated by the dotted part of the thickness line, but they will continue to increase with decrease of the rate of air supply.

(4) An equilibrium fuel bed will result when operating at any point within the area enclosed by curve *abd.* An increase or decrease of the rate of feed—provided it does not cross the curve *abd*—will result in a gradual change to a new rate of burning and thickness of fuel bed corresponding to the new rate of feed.

(5) If an increase in rate of feed crosses the curve *abd,* the rate of burning will not increase beyond that fixed by the curve *abd;* if it crosses the portion *ab,* the thickness of the live fuel bed will increase continuously; if it crosses the portion *bd,* the thickness of the live fuel bed will not increase beyond that for *bd* but the plane of ignition will gradually be raised by the unignited fuel below it.

Fig. 7 shows the rate of ignition and rate of burning curves for the four sizes of coke when using air at 80 fahr.; to avoid crowding, the thickness of fuel-bed curves are shown in a sepa-

rate plot, Fig. 8. The test points are shown and it will be noted that fairly symmetrical curves can be drawn to fit the points.

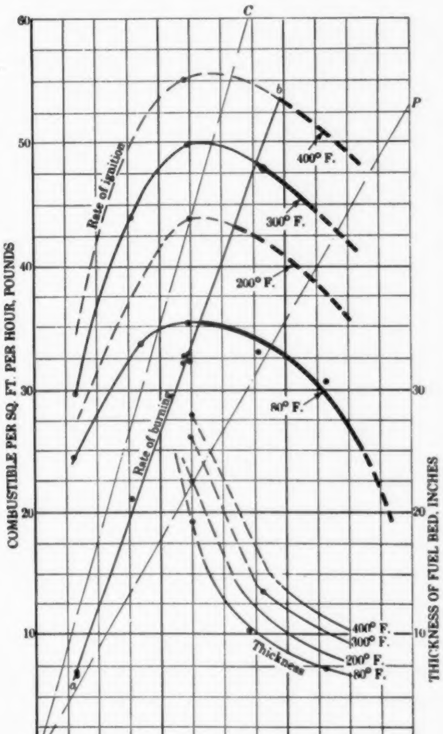

Fig. 10—Underfeed burning, high temperature coke, 1-1½ in. size with rate of primary air and its temperature as variables.

It is of interest that the rate of burning curves previous to their intersection with their individual rate of ignition curves all fall on a common curve which bends upward slightly for the smaller sizes as would be expected from previous investigations on the effect of size.

The figure shows that the rates of ignition increase rapidly with decrease in size, which is in agreement with common experience when starting a fire in one's home furnace. The relationship, based on the points of intersection of the ignition and burning curves, is of the order shown by Fig. 9.

If the air rates were carried high enough, the ignition curves may be expected to have a shape like that of the 2-2½ in. size. An attempt was made to burn this size at an air rate of 345 lb. There was difficulty in getting the fuel to start burning; by using larger quantities of igniting fuel and reducing the air rate, it was ignited, but when the air rate was increased to 345 lb., the burning gradually decreased and finally the fire was extinguished. This showed that ignition could not be maintained.

With this fuel, the rates of burning that can be attained are very much affected by the size of the pieces. With the 2-2½ in. size, the maximum rate of burning possible was 21 lb., whereas with the ½-1 in. size it was 48 lb. This shows a fundamental difference between overfeed and underfeed burning principles; in a hand-fired furnace any size of coke can be burned continuously at any rate by keeping the fuel bed deep enough.

It must be remembered that the curves of Fig. 7 are for the conditions used in these tests, and that the cooling by the sidewalls affects the results. It is not probable that it influences the rate of ignition materially, but it does lower the average rate of burning because of the poorer combustion at the sides. For an absolute value—that is, for a fuel bed of very large area—the rate of burning line *ab* would be swung somewhat to the left. However, it could never cross the line *OC*, which corresponds to a dry-gas analysis for this fuel containing only CO and N_2—that is, one with the maximum carbon content.

The curves for the pounds of secondary air required per pound of primary air are not shown because this is fixed by the position of each rate of burning point on the plot. All points on the line *OP* have perfect combustion; those to the left of the line require secondary air, and those to the right have excess air. The scales on the top and sides permit of reading off the secondary-air requirement at any rate of burning.

It is worth while to grasp fully the meaning of the type of chart represented by Fig. 7 because it is used for all results and because it is interesting and informative. Considering the curves for one size of coke—the 1½-2 in., for example—it has been shown that one can operate continuously anywhere within the area *ace*. Selecting, then, any point of operation, 17.5 lb. of combustible per hour and 200 lb. of air, for example, this point fixes the rate of combustion and the deficiency or excess of air. This is true independently of whether the fuel bed is in a good or bad condition, but it does not show how complete the combustion was; for instance, the dry gas analysis for this example might be 20.0 CO_2, 0.8 CO, 0.0 O_2, 79.2 N_2, or it might be 12.3 CO_2, 7.8 CO, 3.5 O_2, 76.4 N_2. In the latter the oxygen is available and whether the CO is burned will depend on the action in the combustion space. A fuel bed which gives the first of the two analyses would be classed as being in a good condition because the loss of heat due to free combustible in the gases is reduced to a minimum; the second shows that there were holes in the bed or leakage at the sides. This is elementary and not novel; also, the same type of diagram could be used for overfeed burning.

It is also necessary to define the terms "primary air" and "secondary air." Primary air as used in this report means the air supplied below the bed. In the method of test employed, all the air passed through the plane of ignition and also through the whole of the live fuel, although even in these tests its distribution over the area of the bed was not uniform. In stokers the distribution of the air is more complex and at moderate ratings the plane of ignition not as definite; however, if a stoker operates continuously with the same shape of bed, then the rate of ignition—however we may define or explain that action—must be equal to the rate of burning.

The secondary air in these tests is that which might be supplied and mixed with the gases over the fuel bed. In a stoker some of the air supplied below the fuel bed may not pass through any fuel, so that, correctly speaking, it is secondary air. It seems to be the usual custom to apply the term "secondary air" only to that which is purposely supplied over the fuel bed, and to that which leaks through the setting.

If one assumes that in a stoker no air is supplied over the fuel and that it is desired to have 20 per cent excess air in the flue gases, then one is limited to operating along the 20 per cent excess air line of Fig. 7. If all this air passes through the plane of ignition, the maximum rates of burning possible with each size is reduced to the value given by the intersection of each curve with the 20 per cent excess air line. A higher maximum rate of burning could be obtained with each size by passing a smaller weight of air through the plane of ignition and supplying some more as secondary air in its meaning as defined above.

Fig. 8 shows the thickness of the fuel beds. It will be noticed that the curve for the ½-1 in. coke falls out of order. There are two factors which influence the thickness; one, the rate of ignition which tends to increase it, and the other, the rate of reaction which tends to decrease it with decrease in size. A previous investigation(*3*) shows that the second factor increases very rapidly for decrease in size below 1 in.

Effect of Preheating the Air on the Underfeed Burning of High-Temperature Coke. The air temperatures used were 80, 200, 300 and 400 fahr. There was no necessity to test all sizes because the characteristics will be similar; therefore only the 1-1½ in. coke was used.

Fig. 10 shows the results; the lines *OC* and *OP* have the same

meaning as in Fig. 7. The parts of the rate of combustion curves falling on the line *ab* are not materially affected by the preheat; because the same size of coke is used, *ab* has not an upward bend and is nearly a straight line to the origin.

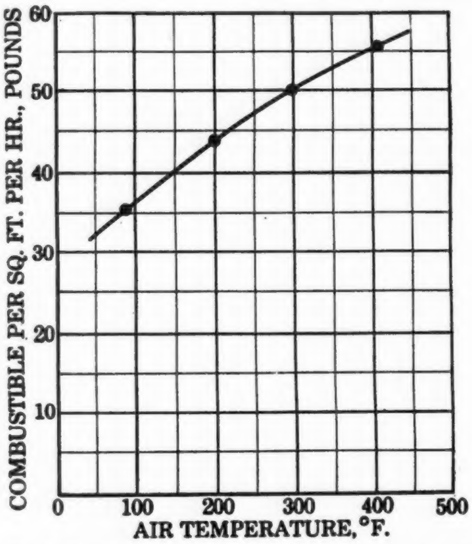

Fig. 11—Underfeed burning, high temperature coke; rate of ignition against temperature of air.

The rates of ignition increase rapidly with increase of air temperature. Fig. 11 shows the maximum values plotted against air temperature; at some higher temperature the curve would turn upward very rapidly because at a certain temperature—probably between 1100 and 1200 fahr.—the coke would ignite spontaneously.

Fig. 10 shows that preheat will have little effect on operation at rates of air supply below that at which the ignition curve meets the burning curve. Above the rate of air supply where the ignition curve for normal air temperature (80 fahr.) meets the burning curve (265 lb. of air), preheat permits of large increase in the rate of burning with a given rate of air supply—but, of course, with the necessity of increasing the secondary air.

The lower set of curves of Fig. 10 show the thicknesses of the live fuel beds for which, however, there were not many test points. The full-line portion indicates that the burning is in equilibrium. The fact that for the same rate of air supply the thickness increases with increase in temperature of the air, at first sight, may seem an anomaly. The explanation is that the increase in the rate of burning that occurs with the preheat requires a thicker fuel bed for equilibrium burning; the increase thus required is more than can be offset by the increase in the rate of reaction resulting from the preheat. Fig. 2 illustrates this, but to a different scale.

Underfeed Burning Tests of Low-Temperature Coke

Low-temperature coke is a good example of a truly non-caking fuel with relatively high volatile content. The coke used was a fairly dense and non-fragile type; its properties were as follows:

Proximate Analysis, per cent:

Moisture	3.4
Volatile matter	13.7
Fixed carbon	72.0
Ash	10.9

Ultimate Analysis, per cent:

Hydrogen	3.5
Carbon	73.4
Nitrogen	1.5
Oxygen	9.8
Sulphur	0.9
Ash	10.9

Softening Temperature, fahr	2721
Weight per cubic foot of 1–1½ in. screen size, pounds	28.3
Pounds of coke per pound of combustible	1.25

The tests made were confined to the 1–1½ in. size. The main series were at increasing rates of air supply without preheat; these were followed by single tests at the same air rate but increasing preheat.

Fig. 12 shows the results plotted in the same manner as were those of the high-temperature coke. The line *OP*, as before, is that of perfect combustion for a fuel with the foregoing analysis. The line *OC* shows the maximum rate of combustion. The rate of ignition curves for 210 and 300 fahr. air temperature are each based on one test point, but their general shapes will be somewhat as shown.

The plots do not differ in their general relationships from those of Fig. 10 for high-temperature coke, and the principles that would be deduced are the same. The slope of the rate of burning line *ab* is a little steeper than of Fig. 10, that is, the gases contain more combustible per pound of air; the main difference is that the rate-of-ignition curves are higher and do not fall off after they reach a maximum. The air rate was carried to 680 lb. to see whether the ignition would not fall off, but it did not; to have gone higher would have meant blowing fuel out of the bed. The interpretation of this is that the fire with this low-temperature coke cannot be extinguished as it could with the high-temperature coke.

The increase of the rate of ignition by the same preheat was greater than that with the high-temperature coke. A test with an air temperature of 400 fahr. was included, but the coke ignited spontaneously in the center of the bed. This does not mean that the average coke would ignite at this temperature, but that exothermic reactions occurred in some individual pieces.

For the same air rate the thickness of the fuel bed was increased by the preheat, as it was with the high-temperature coke.

Although this coke is easily ignited, yet the principle still

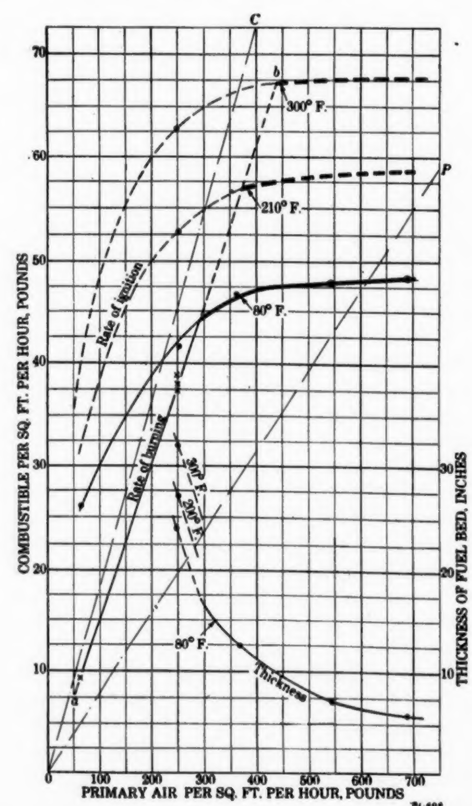

Fig. 12—Underfeed burning, low temperature coke; results for 1–1½ in. size, without and with preheat.

holds that its rate of burning on the underfeed method did not exceed a certain maximum, which for this 1–1½ in. size, without preheat, is 49 lb. of combustible per sq. ft. per hr.; for the high-temperature coke of the same size it was 35 lb.

Underfeed Burning with Anthracite. A complete set of tests have not as yet been made with anthracite, but three different kinds of anthracite were tested at one rate and without preheat to see if they would give their relative ignitibilities for use on another investigation. The size used was 1–1½ in. sq. mesh screen and the rate of air supply 240 lb. of primary air per sq. ft. per hr. A few of the results are given in Table I.

TABLE I—UNDERFEED BURNING, ANTHRACITES

Item	No. 1	No. 2	No. 3
Volatile matter, per cent	3.2	3.8	8.3
Fixed carbon, per cent	82.5	79.4	78.3
Ash, per cent	11.0	13.2	12.2
Weight per cubic foot, pounds	53.0	51.2	46.3
Primary air sq. ft./hr., pounds	240	240	245
Rate of ignition sq. ft./hr., pounds	27.4	27.8	39.2
Rate of burning sq. ft./hr., pounds	27.4	27.8	37.0
Thickness of fuel bed, inches	15.0	15.7	10.5

Anthracites 1 and 2 both burned with equilibrium fuel beds because in each test the rate of burning is equal to the rate of ignition. The rate of burning of anthracite 3 was less than its rate of ignition, and therefore the air rate was too low to give equilibrium. Fig. 6 shows that the same size of high-temperature coke also burned in equilibrium at the air rate of 240 lb. and that the ignition and burning rates were 35 and 33 lb., which are a little below those of anthracite 3.

This measure of ignitibility shows that No. 3 was 43 per cent more easily ignited than No. 1 or No. 2. These comparisons are on the weight of combustible basis; to the eye the coke would appear to ignite 1.6 times as fast as anthracite 1; that is, the plane of ignition of the coke travels faster because of the relative densities and ash contents of the two fuels.

Underfeed Burning with Bituminous Coals. It was realized that more difficulty would be experienced in obtaining reliable data with coals which fuse and cake, but earlier tests (*6*) had shown that they could be burned with equilibrium fuel beds by igniting the bed at the top, provided the air rate was high enough and the coal of uniform size.

The troubles, caused by uneven burning, that were encountered in the individual tests will not be described but they can be summarized as follows. When burning at low rates of air supply, the plane of ignition advanced downward at such a rate that the tar exuded from the coal was not consumed and thus it would tend to close up the air spaces; or the surface of the coal pieces would not be burned away fast enough to make up for the swelling and consequently the spaces were closed. Either of these actions is cumulative because, as the spaces started closing, the air would divert from the center and thus the quantity of air passing through the center would be reduced; this further reduced the rate of burning and allowed more closing of the spaces. As the air rate was maintained constant, that passing up the sides would be increased, or sometimes a hole or channel would develop along the sides which might be straight, but usually had a somewhat spiral form.

At some rate of air supply the bed would burn uniformly and act in the same manner as the cokes. Tests could not be made with the rates close enough together to determine the exact rate at which this change occurred but it appeared to be comparatively sudden, as would be expected from the cumulative action referred to. A uniform burning can be interpreted to be such a rate of air supply over the surfaces that all volatile matter is burned as soon as it is evolved, or in which the rate of burning is greater than the rate of swelling.

Good data could be obtained in the tests in which the rate of air supply gave equilibrium burning, but in the tests below this rate there was no certainty as to the air rate to use for the ignition except that it should be lower than that of the known air supplied; also, the rate of burning obtained from the gas analysis was not that of the whole fuel bed.

All the coals were crushed and screened over square mesh to definite sizes; some of the sizes used were larger than would

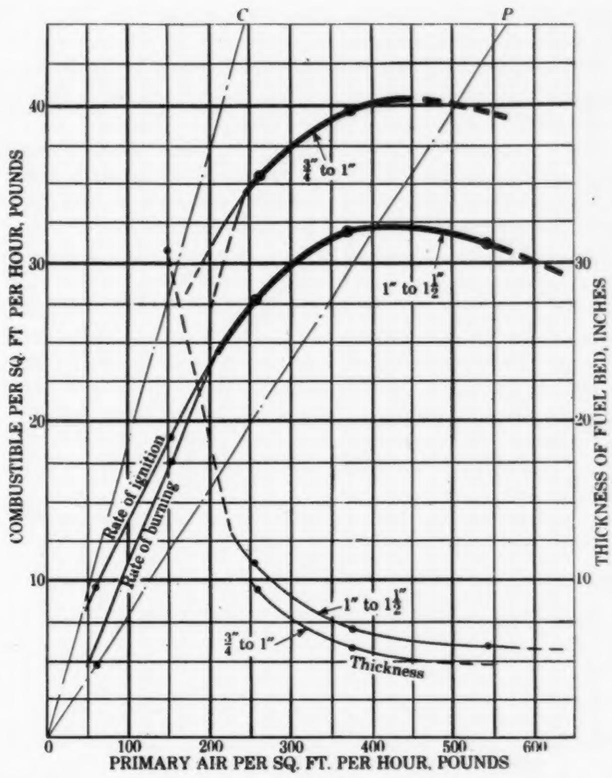

Fig. 13—Underfeed burning, Illinois coal with rate of primary air and size as variables.

ever be employed in underfeed stokers, but it was desired to obtain data which could be compared with those of the cokes to facilitate generalization.

Table II lists the properties of the bituminous coals tested. When different sizes were used the analyses differed somewhat but not enough to affect comparisons of the results.

TABLE II—BITUMINOUS COALS USED IN UNDERFEED TESTS

Name, designation	Illinois	Pittsburgh	Splint	Westmoreland
State	Illinois	Pennsylvania	Kentucky	Pennsylvania
County	Franklin	Allegheny	Harlan	Westmoreland
Bed	No. 6	Pittsburgh	......	Pittsburgh
Proximate Analysis, per cent				
Moisture	6.5	1.7	3.1	1.3
Volatile matter	35.1	34.7	37.0	32.3
Fixed carbon	50.4	55.8	55.3	58.5
Ultimate Analysis, per cent				
Hydrogen	5.5	5.2	5.8	5.2
Carbon	68.8	77.2	77.5	77.5
Nitrogen	1.5	1.5	1.5	1.5
Oxygen	14.1	7.2	10.1	6.9
Sulphur	2.1	1.1	0.5	1.0
Ash	8.0	7.8	4.6	7.9
Calorific value, B.t.u.	12,340	13,780	13,800	13,850
Softening temperature, fahr.	2203	2780	2510	..
Weight per cubic foot, 1–1½ in. size, pounds	44	44	42	43
Pounds of fuel per pound of combustible	1.37	1.22	1.22	1.22

Underfeed Burning, Illinois Coal. The Illinois coal was tested last but it is discussed first because its caking properties are lower than those of the Pittsburgh coal and the tests were more complete.

Fig. 13 shows the results with two sizes of coal without preheat. The heavy lines indicate the rates with which equilibrium burning occurred. The actual data for rates below equilibrium burning are given but, as explained, these values are associated with the test furnace used and include the factor of the clogging of the bed by the caking.

The plot is exactly similar to Fig. 7 for high-temperature coke and the same deductions as made for coke apply, namely: (1) decrease in size increases the rate of ignition; (2) decrease in size decreases the thickness of the fuel bed; (3) there is a maximum rate of burning which cannot be exceeded, which

was 32 lb. for the 1–1½ in. size, as compared with 35.5 lb. for the high-temperature coke.

It would seem that the rate of ignition tends to decrease with very high air rates, similar to that which occurred with high-temperature coke but to a lesser degree.

Fig. 14 shows the results for the 1–1½ in. Illinois coal with various preheat temperatures. Again, the general plot is similar to Figs. 10 and 12 and the increases in the rate of ignition by the preheat are of the same order.

The light line designated as rate of burning has not exactly the same meaning as it had in the plots of the coke tests; rather it is the dividing line between non-equilibrium and equilibrium burning, as fixed by there being no clogging of the bed by caking. This means that the tar that is exuded from the pieces of coal is consumed as fast as it exuded, or that the rate of burning at the surface counteracts the swelling. Thus the coal acts as a free-burning fuel and the area of the figure which is designated as equilibrium burning could be called the free-burning area.

A test was attempted with 400 fahr. air temperature; it will be seen that the point for the test falls to the left of the

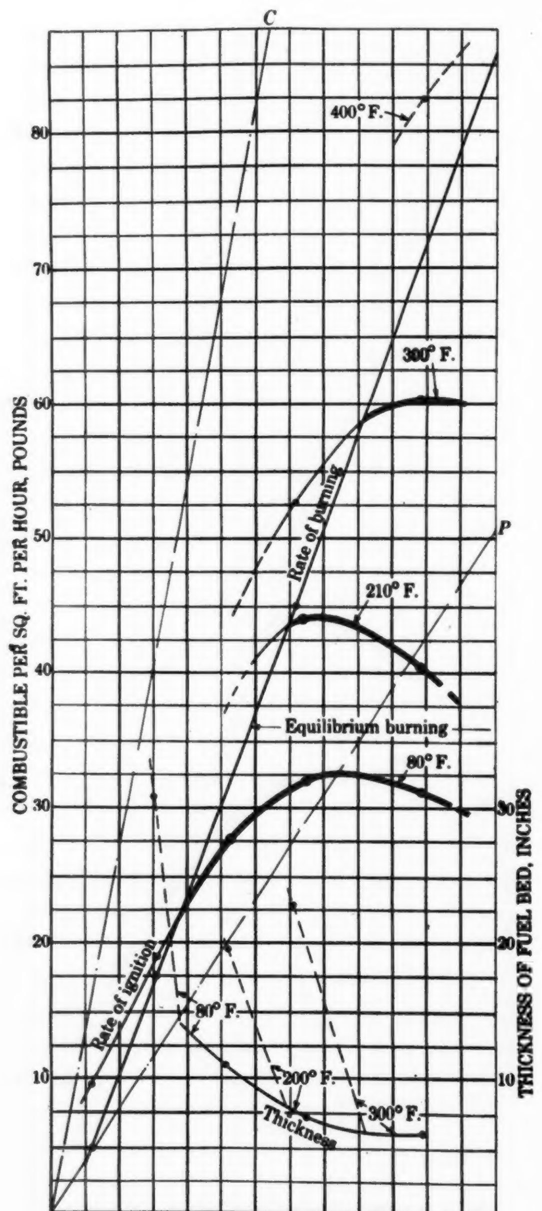

Fig. 14—Underfeed burning, Illinois coal, 1–1½ in. size; with rate of primary air and temperature of air variable.

equilibrium line. The test started out well but when the ignition line had fallen 20 in., almost suddenly the bed clogged up tight and no air could be forced through it with the pressure available; the rate of ignition given is approximate.

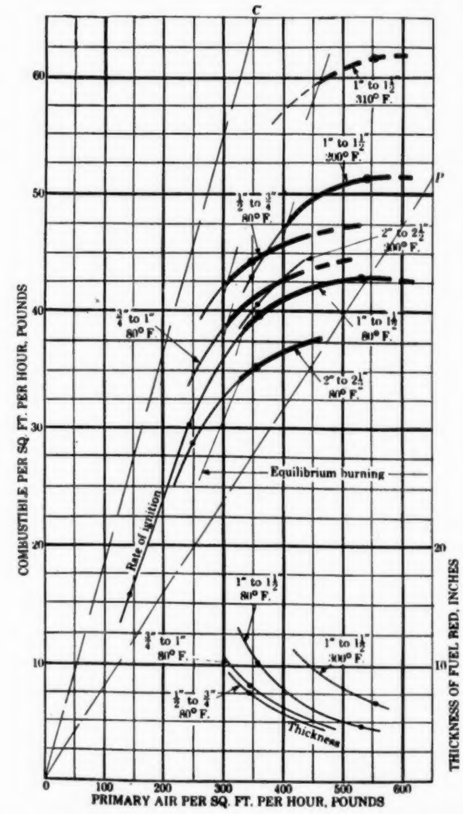

Fig. 15—Underfeed burning, Pittsburgh coal.

The dotted parts of curves for the thickness of the live fuel bed indicate non-equilibrium burning; the thicknesses for equilibrium burning fall approximately on a common curve.

It is obvious that if the caked fuel had been broken up as quickly as it was formed, then the light-line curves would have been swung to the left, and the shapes of the curves would have been more similar to those for the cokes.

Underfeed Burning, Pittsburgh Coal. This being the first bituminous coal tested, attempts were made to improve the method and procedure. To obtain accurate data on the non-equilibrium burning it was necessary that the air supplied should pass uniformly through the area of the bed instead of being diverted to the sides by the caking. Attempts were made to insure this by increasing the resistance of the bed at the sides by packing it with small-size coal, so that the coal being tested formed a core 16 in. in dia. with a ring of fine coal around it 2 in. in thickness; it was accomplished by using a 16-in. dia., sheet-iron cylinder 12 in. long, and gradually building up the bed.

This kept the center of the bed more open, but it did not entirely eliminate the clogging, and the small coal at the sides also burned out more rapidly or channels were formed. However, this method did increase the rate of ignition in the low air rate, non-equilibrium area as much as 100 per cent. As would be expected, it made little difference in the equilibrium area but increased the ignition rate a little, both because of the effect of the small-size coal and because—even with a uniform fuel—there is always less resistance to air flow at the sides.

A variety of tests were made with the Pittsburgh coal, the majority with small fuel at the sides. Fig. 15 shows plots of most of the tests, both for different sizes of fuel and for different air temperatures. The order of the results is the same as for the Illinois coal; with the same size coal, 1–1½ in., the maximum rate of burning possible without preheat was higher, 43

to 32 lb.; with 300 fahr. air temperature the maximum rate of burning was about the same, 61 lb. As before, the rate of ignition decreased with increase in size; the sizes were carried to the $2-2^1/_2$ in. screen.

There is no common line fixing the division into equilibrium area; those drawn in the plot can only be considered approximate. It is certain, however, that the line is further to the left for the smaller coals; this can be interpreted to mean that the openings between coal pieces can be kept clear more easily as the size of the coal decreases. Knowing that it occurs, an explanation can be given, but one's first guess would probably be the reverse.

There is no necessity to discuss the results of Fig. 15 in detail.

Underfeed Burning, Splint Coal. Splint coals differ from other bituminous coals in that they do not fuse when heated. On the other hand, they exude their volatile matter as a tarry substance, which will tend to fill the air spaces. It is not known whether splint coal is used on large underfeed stokers, but it has been used in domestic stokers. The coal was not specially obtained but was tested because it was available and because it had distinctive properties.

All tests were with $1-1^1/_2$ in. size, the temperature of the air being varied. Fig. 16 shows the result. All tests are for beds packed with small coal at the sides, except for the two tests indicated by crosses. Thus tests A and A′ are duplicates except that the latter had no packing; their positions indicate the order of the difference obtained by the two methods.

The results show the same relationships as for the other fuels, but the line fixing the equilibrium area is further to the left, thus giving a larger equilibrium area. The maximum rate of burning possible without preheat is decidedly greater than the rates for the other bituminous coals, being 51 lb. as against 42.5 lb. for the Pittsburgh. However, the increase in the rate of burning by the same preheat is about the same as for the Illinois and Pittsburgh coals.

At non-equilibrium rates this coal burned around the sides, leaving a solid pillar of coke in the center. It would seem that the tarry matter filled up the spaces and coked, but the whole coked mass did not tend to open up cracks as much as in the other two coals, and thus little if any air passed through the center mass.

A test on this coal was also tried at 412 fahr. air temperature and a rate of 535 lb. of air. It burned for a time and indicated a rate of ignition of about 100 lb.; it then clogged up very rapidly, but not so quickly as did the Pittsburgh coal at 400 fahr. This clogging would be expected because Fig. 16 shows that the point of operation used lies outside the equilibrium area.

Summary of Underfeed Tests. There is no necessity to make a detailed summary, nor at this time will this method of test as a means of determining the burning characteristics and of comparing fuels be discussed in full. There is one characteristic important in the operation of stokers which the method does not measure—namely, the ease of breaking up the caked or coked masses. It can be imagined that this quality is compounded of tensile strength and brittleness as measured by elasticity.

The results justify the method of attack used of thoroughly testing high-temperature coke first, as the clear viewpoint this gave of the relations between quantities set a standard for interpreting results with fuels which were more difficult to test.

Because the fuels had been in dry storage, their moisture content was low. Some study of the effect of moisture on the rate of ignition is of interest.

Reactions in an Underfeed Fuel Bed

It was desirable to have records of the reactions in fuel beds burning on the underfeed principle which would show the same data as does Fig. 2 for overfeed. These tests involve some difficulties because the zone of burning is moving, but complete data were obtained for the high-temperature coke and for the Illinois coal, the latter including tar and soot determinations.

The complete results are not given in this report; they present a good picture of what occurs in the bed and how the ignition progresses. The following are some of the conclusions one can deduce.

(1) In an underfeed bed heat is abstracted from the lower part of the burning zone to heat up the incoming fuel so that reactions all through the bed lag because of this abstraction of heat.

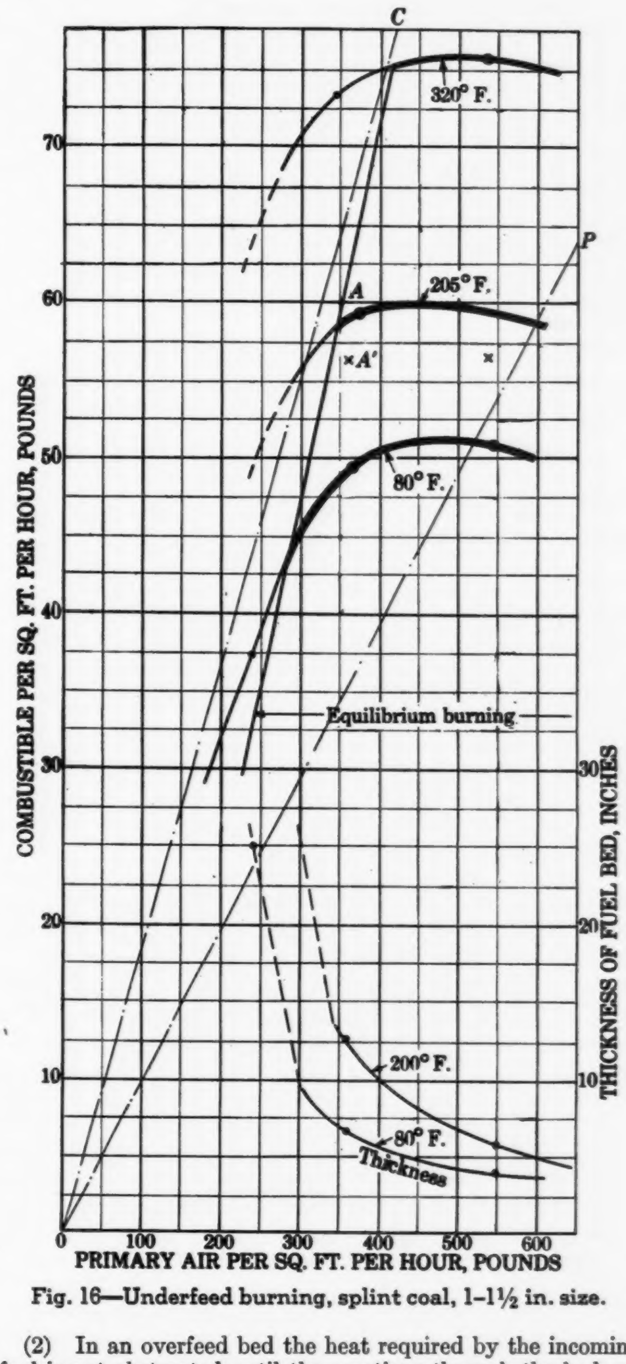

Fig. 16—Underfeed burning, splint coal, 1-1½ in. size.

(2) In an overfeed bed the heat required by the incoming fuel is not abstracted until the reactions through the bed are completed; although the same quantity of heat is required as with the underfeed, and the temperature of the outgoing gases is lowered, this does not affect the reactions in the bed below.

(3) The fact that the fuel is being heated up and is of a larger size at the ignition end of an underfeed bed reduces the rate of reaction, or, in other words, lengthens the time required for the same total reaction more so than for the overfeed bed, where the rate of reaction is very slow, as is shown by Fig. 2.

(4) Consequently, for the same rate of air supply, and the

same weight of combustible per pound of air carried by the exit gases—that is, the same rate of burning—the equilibrium depth of an underfeed bed will be greater than that of an overfeed.

The last conclusion will be correct for normal operating conditions but a full discussion would be long.

To give an idea of the burning of the underfeed bed when using high-temperature coke, the dotted curve was added to Fig. 3; the rate of air supply in the underfeed tests was the same as that in the overfeed. The relative positions of the 80 fahr. curves illustrate the above conclusions.

That the process of ignition hampers the burning in an underfeed bed was shown in a number of tests made at air rates for which the rate of burning was less than the rate of ignition, and the thickness of the live bed was continually increasing; in these tests the rate of burning was approximately constant when the plane of ignition reached the grate. When it reached the grate, and there was no more fuel to ignite, the rate of burning increased very rapidly, although the air rate was not changed. This increase with the cokes was sometimes more than 50 per cent; with the bituminous coals there was sometimes no increase because at low rates the burning was not uniform over the area of the bed.

Evidences of this action should occur in stokers; when at low rates the coal feed has been too rapid, and it is stopped, then the boiler output may be expected to rise temporarily.

Application of Results to Underfeed Stokers

Some deductions on how the experimental burnings are related to the actions which occur in the fuel beds of underfeed stokers have been suggested in the previous part of this report. All the tests were made with unrestricted ignition, and it was shown that the burning which results is the maximum which can occur with each rate of air supply, and that with a given rate of air supply a restriction of the rate of feed below its corresponding rate of ignition will result in a thinner fuel bed and a rate of burning equal to the rate of feed, together with a reduced requirement for secondary air.

It was also shown that the main difference between overfeed and underfeed burning is that with the former the rate of burning can be increased indefinitely, provided the fuel is not blown out of the bed, but with the underfeed there is a limitation to the rate fixed by the rate of ignition.

No attempt will be made to picture completely what goes on through the length of the fuel bed of a large underfeed stoker because that would necessitate defining the paths of the various streams of incoming coal and the distribution of the air. Presumably some coal may have a superimposed vertical motion, and undoubtedly, even in the same stoker, the actual paths will not be the same at all rates and with different coals. In addition, the distribution of the air flow through the coal will depend on the caking and on how the caked coal is broken up by the motion. However, one can draw some conclusions as to possibilities, especially for rates of burning near the limit of the ignition rate because this is the range covered by these tests.

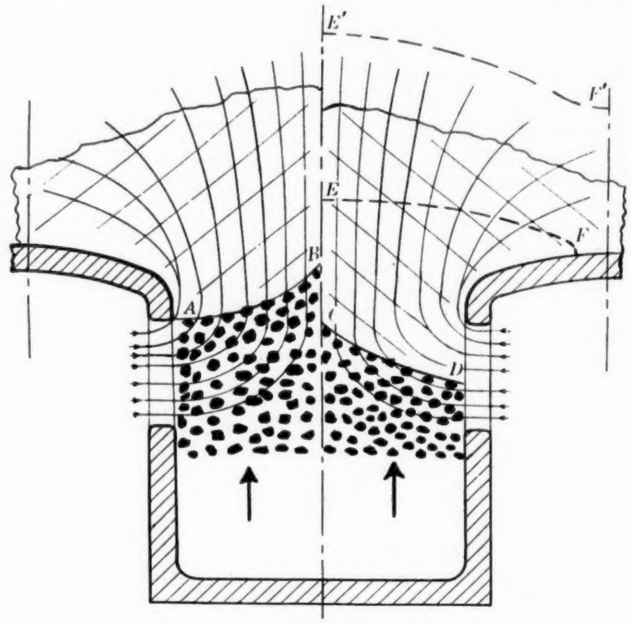

Figure 18

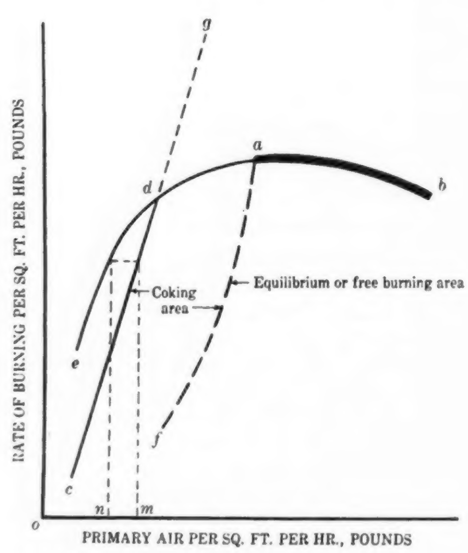

Fig. 17—Diagram of operation.

Considering Fig. 17, the line *ab* corresponds to the heavy lines of one of the figures for bituminous coal, and it gives the rate of burning with unrestricted ignition in a quiet, that is unagitated, fuel bed; because a caking coal burns as a free-burning fuel along this line, presumably the burning would not be changed even if the bed were agitated. Considering still the unagitated bed, and assuming that one is operating at the feed and air rates of point *a*, if one began to restrict the rate of feed and to reduce it below the ordinate of point *a* and at the same time to reduce the air rate just enough to maintain the non-caking, or free-burning condition, then probably one would move along some curve *af*, although this suggestion is not based on experimental data. Therefore, with a non-agitated bed, operation anywhere in the area *fab* would be free-burning.

Assuming that the bed were agitated enough to keep the fuel pieces free from each other, then the curves for unrestricted ignition would be similar to those for a non-caking fuel, such as *cd* and *edb;* it follows that with a restricted feed, operation with an equilibrium bed would be possible anywhere within the area *cdb*.

These deductions are based on the assumption that the air passes through the incoming coal and keeps it cool; if it did not, and if the coal were heated up and coked before it reached the air stream, then, unless this coke were broken up, the deductions would not hold.

One has to use more imagination when trying to picture a cross-section of the fuel bed of an actual stoker, but one is on safer ground if the stoker is operating at the limit of its ignition rate—that is, on the line *db* of Fig. 17 for an agitated bed. Fig. 18 represents a section of a stoker operating at maximum rate, but on the assumption that the fuel is moving vertically.

Assume that the coal feed has brought the ignition plane to the position *AB* shown in the left-hand half; then the conditions of ignition are the same as those of these tests, and the same values should apply. The rate of air supply per square foot would be fixed by the area of the surface *AB*, and the rate of ignition by the ordinate of the point on *db* of Fig. 17 which

corresponds to the air rate. If the coal feed were reduced for a time so that the ignition line fell to what would probably be the line *CD* of the right-hand half of Fig. 18, then the average air flow through the ignition plane would be reduced—although the total air was not changed, and the measure of the ignition rate would move along the line *bd* of Fig. 17; as it approached *d*, the rate of ignition, and consequently the rate of burning, would decrease. With a fixed rate of coal feed and air supply it is probable that the plane of ignition would find some position along the height of the air slot which would produce equilibrium.

As one tried to push the output by increasing the coal feed, it can be conceived that the line of ignition might be raised to *EF* with the top of the bed as shown dotted; because this increases the area of ignition, a corresponding increase in the maximum rate of burning would be possible.

It must be recognized that in all these illustrations there is no question about the ability to burn the coal; as long as one is operating—for an agitated bed—along the line *db*, the rate of burning for any rate of air supply could and would be limited only by the line *dg* if it were not that it is limited by the rate of ignition line *db*. It does not matter whether the stoker is a simple pot, which was the type used in these tests, or whether the fuel flows over the side, as is represented in Fig. 18. With continuous operation, the height and shape will adjust themselves to give a rate of burning equal to the rate of ignition.

Although non-caking fuels are not burned in underfeed stokers, yet it is of interest to extend the argument of the last paragraph to what would occur at low ratings. If a non-caking fuel were being burned under conditions represented by Fig. 18, and if the rate of air supply were less than that of point *d* of Fig. 17, under continuous operation the ignition plane would find some level like *CD* of Fig. 18 which would make the rate of ignition equal to the rate of burning. If in Fig. 17 the total quantity of air supplied is *om*, the quantity passing through the ignition plane would be *on*, and that above the ignition plane, *nm*.

In the foregoing discussion of the ignition in an agitated bed it was assumed that the caked or coked coal is well broken up by its movement. This will not occur with a good caking coal

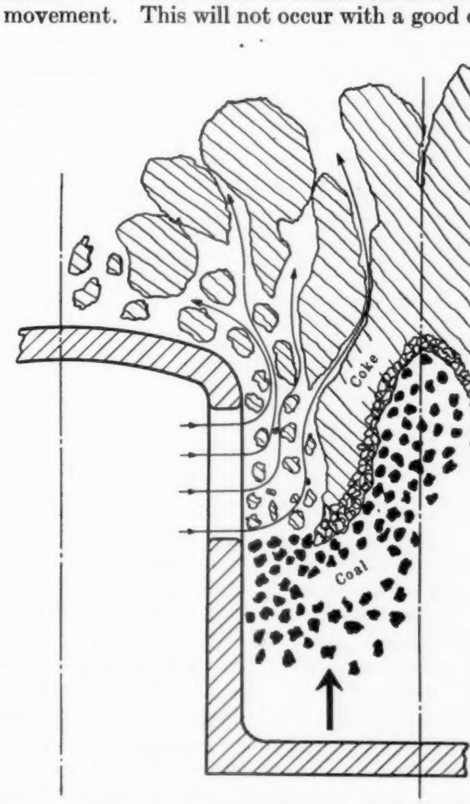

Figure 19

and the motion will split the mass into relatively large pieces. The result will be that most of the coal will not come in contact with air until it has been coked and that most of the actual ignition will occur at the surfaces of the large coke pieces. Fig. 19 presents such a conception. Because of the large size of the pieces of coke the equilibrium depth of the bed must be greater to allow enough area of the surface of the fuel for the reactions to occur. The fuel around the air slot will be consumed more rapidly, thus undermining the coke mass so that it may fall over.

At low rates of coal feed for which the point of operation would fall well below the line *cd* of Fig. 17, the rate of ignition would be large compared with the rate of burning. The ignition line would sink as low as it could but it could not go below the air stream line; however, the coal below the ignition line would be heated by radiation and conduction and would not be cooled by the air stream, and, consequently, it would coke and its volatile would rise into the air stream. Although the volatile would be ignited and burned, yet the remainder of the coal, or the coke, cannot be said to be ignited until it rises and its surface meets the air stream. If the conditions are as conceived in Fig. 19, there is no definite plane of ignition, but at low rates the actions will undoubtedly be somewhat as depicted. It would be under such conditions that the coking qualities of the coal and the agitation it gets would be of the most importance in determining the fuel bed that would result.

The following generalization on large stokers is probably warranted: The more usual mode of operation as represented by a humped fuel bed implies that the type of bed is an enlargement of that represented by Fig. 19, with possibly a small part as represented by Fig. 18. This will mean that a deep bed will be required to present a large enough surface area of coke for the ignition and burning actions. A type of bed as advocated by Mr. Houghton (*4*) is premised on a design and on a method of operation which will distribute the plane of ignition over a larger area of the bed, so that more of the action will correspond to that represented by Fig. 18. This mode of operation should permit of more even distribution of the air, result in a thinner fuel bed and the composition of the gases arising from the fuel bed should be more uniform; one would also expect that the bed can be better controlled to make the analyses of these gases conform more nearly to the average desired, and to require less mixing of the gases in the combustion space.

Effect of Fuel Size in Underfeed Stokers. The effect of the size of the coal pieces on the burning in a stoker will depend on the rate of burning. When working at high ratings, as illustrated by Fig. 18, a decrease in size will permit of an increase of the maximum rating possible, neglecting, of course, limitations to the quantity of air that can be forced through the bed because of increase in resistance with decrease in size. When working at low ratings in which masses of coke are formed, the first effect will not come into play, and then it can be presumed that the effect of size will be that larger sizes will give a better chance for the air to penetrate into a mass when it is only partially fused together and is not fully coked; this will mean that the mass will be partly burned and, therefore, more open and fragile.

Effect of Preheat in Underfeed Stokers. The results of the use of preheat with underfeed stokers have been described in a number of papers by operators, and the subject has also been debated extensively. It is therefore worth while to attempt to interpret the results of these tests. The argument will be itemized.

(1) Neglecting the effect of ignition and considering only the effect of preheat on a fuel bed of a given depth, the tests show that the additional heat contained in the preheated air is utilized partly in increasing the rates of reaction in the fuel bed—that is, in increasing the rate of combustion for the same air rate—and partly in increasing the temperature of the gases leaving the fuel bed. The partition of the total heat into these two portions will depend on the depth of the bed, but approxi-

mately it can be said that 50 per cent goes to each action; all of the data on the underfeed tests on this phase have not been worked up.

(2) As a result of Item 1, there will usually be more CO in the gases and more secondary air will be required.

(3) Presumably the higher temperature of the gases leaving the fuel bed will tend to cause better combustion in the combustion space, but as this increase is added to an already high temperature, it is questionable whether the benefits gained because of the increased temperature of the gases from the preheat will offset the disadvantage that there is more CO in the gases, and thus more secondary combustion action required; moreover, the available higher temperature of the top of the fuel bed and the gases will be lowered because of the increased radiation to the water surfaces. Such questions could only be settled by tests, but the variations to be determined would usually be less than those of operation.

(4) It would thus appear that preheat will give only limited assistance to the combustion. This does not, of course, affect its value as a means of producing an increased overall economy of the system.

(5) The tests showed that the outstanding effect of preheat on all fuels was that it increased the rate of ignition; for example, based on a normal air temperature of 80 fahr., preheating the Illinois coal increased the maximum rate of ignition 35 per cent for 200 deg., and 85 per cent for 300 deg. For Pittsburgh coal the increases were 19 per cent for 200 deg., and 43 per cent for 300 deg.

(6) It would therefore appear that the most useful function of preheat is that it permits of a higher rating being obtained and that a moderate preheat will materially increase the range of output.

(7) No attempt has been made to suggest the position or shape of the ignition plane in the complex fuel beds of large stokers. Still confining our argument to high ratings, for which the ignition would correspond in principle to Fig. 18, it would seem that the quantity of preheat will influence the position of the plane of ignition and might, to some extent, be used to control it.

(8) Because preheat increases the rate of ignition, if the preheat used produces a rate of ignition greater than that required for the rate of burning, then it will in general tend to bring the burning nearer to the metal work of the stoker. Consequently, the burning of stoker parts with preheat may be directly due, not to the increase in temperature because of the added heat, but because the burning of the fuel is nearer to the metal. It would therefore appear that troubles might be lessened by reducing the preheat temperature if it is higher than that required to give the rate of ignition necessary for the rate of burning.

(9) In this investigation it was not possible to make a successful test with 400 fahr. preheat, whereas higher temperatures have been used in service. This is no anomaly, because the method of test necessitated heating up the whole of the coal used and maintaining it at the full temperature for one hour or more. In service the coal will not be heated materially until it meets the air stream.

(10) It is difficult to suggest any advantages because of improvements in burning characteristics resulting from the use of preheat at low rates of burning as represented by Fig. 19. The coal will be more thoroughly coked, and the improvements must be found in the actions covered in Items 1, 2 and 3.

It is recognized that the pictures suggested in the foregoing may not be in agreement with what occurs in a large stoker. A much larger proportion of the coal may be heated, lose its volatile and be coked before it meets an air stream. The pictures may, however, help those who operate such stokers better to analyze what actually happens.

One could use the experimental data of this paper to deduce approximations of the thickness of fuel bed that would occur and the secondary air that would be required for various assumed conditions. However, such data can only be reliably obtained by experimentation with each type of stoker and of coal, and the usefulness of the data presented in this report is limited to presenting a picture which may help in explaining what has been found to happen, or in suggesting the causes of troubles and possible methods for alleviating them.

Ignition on Chain-Grate Stokers

As pointed out in connection with Fig. 4, the length U (the ignition portion) of the bed of a chain-grate stoker is burning on the underfeed principle; the ignition is by radiation. In the tests of this report the top of the bed was ignited by a layer consisting of $1^1/_2$ lb. of charcoal and 2 lb. of petroleum coke, both wetted with kerosene; the fan was started as soon as the kerosene was alight and was at once brought up to the air rate to be used in the test. There may be question as to whether this type of ignition is the same as that by radiation, but there can be little difference except in the rate at which the temperature of the top surface will rise; this will also vary in furnaces, both with type and with rate of operation.

The time required for the ignition plane to travel down the first 4 or more inches would correspond to the similar action on the chain-grate stoker; compounding this rate with the speed of the grate gives the slope of the ignition plane.

The test data on this phase have not been analyzed completely; in general they show that the rates of ignition for the upper part of the bed are of the same order as those given by the curves; the rate of air supply, the size of fuel and the preheat affected the rates of ignition in the same manner, but not to the same degree. The effect of the caking of the coal at low rates of air supply is of interest; caking does not affect the rate of ignition for about the first 4 in. of depth, but below that the bed apparently cakes enough to lower materially the rate of travel of the plane of ignition. This phase may be investigated further by using shallower beds, corresponding to those used on chain-grate stokers.

Personnel and Acknowledgments

This investigation was conducted under the authorization of Mr. O. P. Hood, Chief Engineer, Mechanical Division, U. S. Bureau of Mines. Mr. D. T. Rosenthal, junior fuel engineer, assisted in the investigation from its beginning. Acknowledgments are given to the Philadelphia Coke Company, which supplied the coke used for the overfeed tests; and to Eavenson, Alford and Hicks, Pittsburgh, Pa., which supplied the splint coal.

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The Peabody Engineering Corporation announce the removal of their main offices from 40 East 41st Street to 580 Fifth Avenue, New York City, where they are now occupying the larger part of the 26th floor.

They have also recently taken over a factory in Stamford, Conn., where all Peabody equipment will be manufactured. Notwithstanding the depression, the business of this company has continued in considerable volume, and the new plant has been acquired to meet an unexpected increase and to place the manufacturing under the personal supervision of the Peabody organization.

Correlation of "Grindability" with Actual Pulverizer Performance

By MARTIN FRISCH[1] and G. C. HOLDER[2]

There is a distinct need for some simple laboratory test which would serve as a basis for predicting the performance of coal pulverizers. The authors endeavored to establish consistent relationships between the results obtained from the most satisfactory methods of laboratory test and actual pulverizer performance. They found as the result of comparing the data of a number of pulverizer tests with laboratory grindability tests that systematic relationships exist when the performance data are reduced to a common basis to compensate for the effects of fineness of product, feed size and moisture. . . . The authors recommend that the definition of grindability be simplified to the expression of a percentage through some standard screen.

THE selection of a pulverizer for the disintegration of coal which is to be burned in pulverized form is based on many factors. Some of these are technical; others economic. No matter which of the many available types of pulverizers is finally selected, it is assumed by the buyer and generally guaranteed by the seller that the machine selected will pulverize each hour a required amount of coal to a certain minimum fineness. Quite often the power consumption is stipulated also and the expected rate of wear of the grinding parts predicted.

Until comparatively recently few considered it worth while to make fine distinctions between coals to be pulverized. Bituminous coal was considered synonymous with soft coal on the one hand, and on the other anthracite was considered synonymous with hard coal.

But experience dearly acquired when equipment which failed to meet guarantees had to be either modified or replaced, focused attention on the extreme differences in characteristics possible in apparently quite similar coals. Many "soft coals" were found to be very hard. Also it was found that though of equal fineness some burned more easily in pulverized form than others.

Engineers who find it necessary to do so now classify coals as to their softness or pulverizability and in a general way as to the ease with which they may be burned in pulverized form. These two properties determine the choice of pulverizing equipment. The required fineness as determined by combustion requirements and the pulverizability of the coal determine the type and size of pulverizer most suitable.

Many have realized the need for some simple test which could be carried out in a laboratory in order to reveal and measure some property of a coal which could serve as the basis for predicting the performance of large pulverizers with that coal. Several such test methods have been proposed and many of these are now in the course of development. The most noteworthy and excellent are those proposed by Cross and Hardgrove.

B. J. Cross (*1*)* in 1926 started to develop, later perfected and in 1928 reported to the A.S.T.M. a method involving the treatment of a small representative sample of a coal in a laboratory pebble mill with a standardized charge of steel balls for a definite time at a definite speed. An index number proportional to the calculated amount of new "surface" produced during the treatment was used to classify the coal with respect to other coals as to its resistance to disintegration. Coals whose index numbers were low were considered more difficult to pulverize than coals whose index numbers were high. A relation between the index numbers and the corresponding capacities of roller mills with those coals was established.

R. M. Hardgrove, in a paper (*2*) read before a meeting of this society at Birmingham, Alabama, presented the results of a laboratory investigation of "grindability" of coals of the U.S. The principle of the test was the same as that outlined by Cross, namely, to consider the grindability as a function of the new surface produced as calculated from the results of a test involving the treatment of a small representative sample of a coal for a definite time in a special laboratory "grindability" machine developed during the investigation. Grindability was specifically defined, however, as the ratio of the surface produced during the test to the surface produced when a standard or 100 per cent grindability coal is treated in identical fashion. A relation between laboratory grindability and the actual performance of vertical ball pulverizers was established.

Cross concluded that the results of laboratory grindability tests and actual pulverizer performances must be correlated empirically after making tests of the stated coals in actual pulverizers, while Hardgrove concluded that pulverizer capacities may be considered to be nearly proportional to grindability as defined by him provided that the mill grinding parts were completely scavenged of fines.

Either the Cross or the Hardgrove method may be made to give consistent information about a coal, which information may be useful in predicting qualitatively how a certain pulverizer will act on that coal. But in order to make quantitative predictions as to how that pulverizer will treat that coal it is necessary to establish by test the relation between the capacity of the pulverizer and coals of different grindabilities. One has but to examine the definition of grindability and the meaning of pulverizer capacity to understand that the latter neither need

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* Numbers in parentheses refer to references at end of article.

be directly proportional to grindability, nor the relation between capacity and grindability for one type of pulverizer be the same as for another, or even for all sizes of the same type.

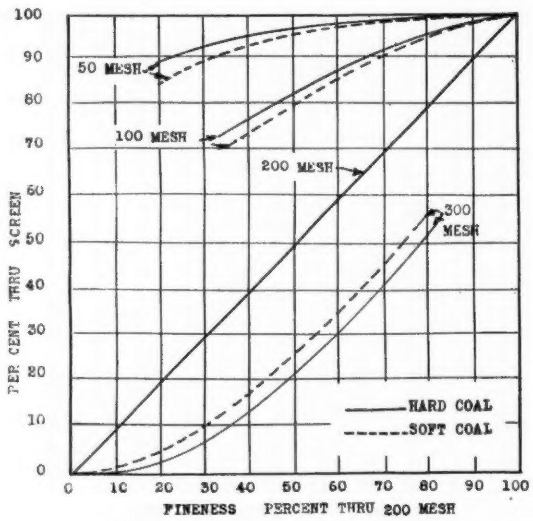


Fig. 1—Relation between results of sieve tests and fineness in per cent through 200 mesh.

If the capacity of a pulverizer were defined as the amount of particle surface produced per hour, then grindability defined as the ratio of the particle surface to the particle surface of a standard coal produced under identical treatments might be considered as directly deducible from Rittinger's Law. But the capacity of a pulverizer is nearly always stated to be a rate of so many weight units per unit time at a certain stated fineness, usually defined by stating the percentage passing through a screen of a certain size. So, unless the specific surface per unit weight of pulverized coal at a stated fineness is the same for all coals, pulverizers which presumably have exactly the same capacity according to the usual definition would not have the same capacity if particle surface were the measure of capacity.

As a matter of fact the amount of surface per pound of coal at a stated fineness is not the same for different coals. If the results of carefully made fineness analyses extending into the superfine ranges of hard and soft coals are plotted against the

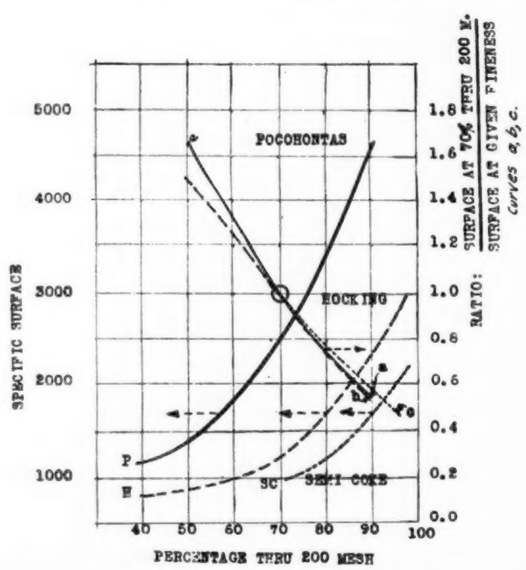


Fig. 2—Relation between fineness in per cent through 200 mesh, specific surface and surface ratios. (Curves P, H and SC are based on Table III, p. 537 of "An Experimental Study of the Burning Characteristics of Pulverized Fuels" by R. A. Sherman.)

fineness in per cent through a 200-mesh screen the explanation for this will be apparent. For it is found that the percentages through screens coarser than a 200 mesh will be higher for the hard coals than for the soft coals and that the percentages through screens finer than 200 mesh will be less for the hard coals than for the soft coals. This is shown diagrammatically by Fig. 1. Consequently, since the specific surface varies inversely as the diameter, the specific surface per pound of soft coal at a given fineness should be greater than for a hard coal. That is to say, a sample of pulverized soft coal will contain more superfines than a sample of hard coal at the same fineness. Fig. 2, based on Sherman's surface data (*3*) obtained by careful microscopic count shows, that at any fineness as expressed by the percentage through a 200-mesh screen the surface per pound of Pocahontas coal, which is very soft, is twice as great as that of Hocking coal, which is quite hard, and more than two and one-half times as great as that of semi-coke. A direct comparison, therefore, between the surface per unit weight of a stated coal after the grindability test and the surface per unit weight of a standard coal will not be the same as the ratio between the capacity obtainable with that coal and the standard coal pulverized to the same fineness, unless in the grindability test the stated coal were pulverized to the same fineness as the standard coal instead of for the same time, as is actually done. This may be demonstrated thus.

If in Fig. 3 we assume that

S = Surface per lb. standard coal at a stated fineness of F per cent through 200 mesh,
S_1 = Surface per lb. of coal No. 1 at a stated fineness of F per cent through 200 mesh,
S_n = Surface per lb. of coal No. n at a stated fineness of F per cent through 200 mesh,
$100\,G$ = Grindability of standard coal = 100
$100\,G_1$ = Grindability of coal No. 1
$100\,G_n$ = Grindability of coal No. n
} Hardgrove's definition,
X = Surface per lb. of coal No. 1 after laboratory grindability test,
Y = Surface per lb. of coal No. n after laboratory grindability test,
Z = Surface per lb. of the standard coal after laboratory grindability test.

And if it be assumed that the ratio of the amount of surface produced after treating a given coal per unit time in the grindability machine to the amount of surface of the standard coal produced after identical treatment is the same as in the commercial pulverizer,

$$\frac{X}{Z} = \frac{C_1 S_1}{C_s S} \qquad (1)$$

$$\text{and} \quad \frac{Y}{Z} = \frac{C_n S_n}{C_s S} \qquad (2)$$

where C_1 and C_n are the capacities obtainable, respectively, with the standard coal and coals Nos. 1 and n in the commercial pulverizer when pulverizing to the same stated fineness F.

$$\text{Since by definition } G_1 = \frac{X}{Z} \qquad (3)$$

$$\text{and } G_n = \frac{Y}{Z} \qquad (4)$$

$$\frac{C_1}{C_s} = G_1\left(\frac{S}{S_1}\right) \qquad (5)$$

$$\text{and} \quad \frac{C_n}{C_s} = G_n\left(\frac{S}{S_n}\right) \qquad (6)$$

$\frac{C_1}{C_s}$ and $\frac{C_n}{C_s}$ may be defined as the true grindability of coals Nos. 1 and n in the commercial pulverizer.

If the ratio of the amount of given coal surface to standard coal surface produced per unit time is not the same for the large pulverizer as for the grindability machine, as for example in a pulverizer which adequately treats soft materials but under-treats hard ones, we must write

$$\frac{C_n}{C_s} = (P)\, G_n \frac{S}{S_n}$$

where P is a function depending on the relation between the characteristics of the commercial pulverizer and of the grindability laboratory test mill.

In general, P will be different for each pulverizer design. It might even vary from time to time for the same pulverizer

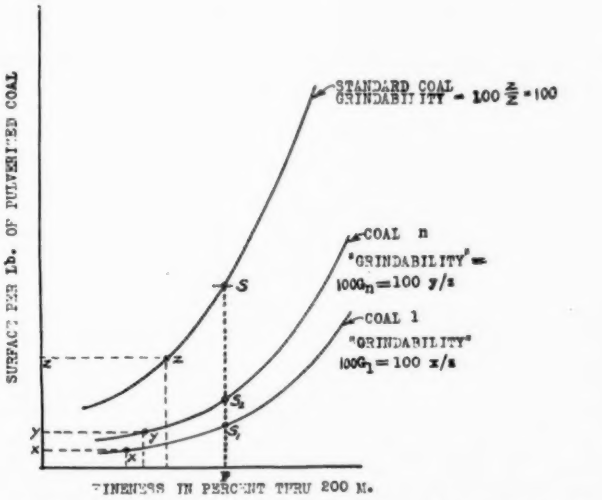


Fig. 3—Relation between surface measured by grindability test and surface at same fineness for three coals.

due to changes in speed, the height of coal level or other operating conditions.

An apparent lack of consistency between actual pulverizer tests and laboratory grindability determinations led the writers to undertake a study of the relationships between laboratory grindability test results and actual pulverizer test data in order to determine whether the two could be reconciled. Grindability tests were made both by a method based on the recommendations of Cross, later simplified, and by the Hardgrove method. Results of a large number of pulverizer tests were completely analyzed by statistical methods and made comparable with each other and with the laboratory tests by reducing them to a common basis as will be explained later. The results presented are confined to a consideration of ball and roller mills only. Impact pulverizer comparisons are not included.

It was found that carefully obtained pulverizer test results can be reconciled with carefully obtained grindability test data.

A direct comparison between actual pulverizer performances and results of grindability tests of unquestioned accuracy of identical coals are too often disappointing only because the data compared are not reduced to a common basis. The grindability test is made on a small dry sample carefully prepared in a prescribed manner and pulverized by a batch process under accurately controlled conditions. On the other hand actual pulverizer tests involving continuous pulverization with or without classification are not so precisely controllable. The size of the feed, the moisture content, the temperature and humidity of the air fed to the pulverizer, the amount of coal in the mill at any instant and the condition of the grinding parts all influence the performance. Furthermore, the fineness of the product leaving the pulverizer has a very marked influence on the actual output of the machine. Consequently, before the pulverizer test results can be compared with the grindability data one must know how to reduce all data to a common basis by correcting the pulverizer test results to offset the effects of variations from standard of

(*a*) Fineness of product,
(*b*) Feed size,
(*c*) Moisture in the feed.

In order to make the results of the various pulverizers herein considered comparable all were corrected to the same fineness arbitrarily selected as 70 per cent through 200 mesh (this being a usual basis for rating pulverizers) and a standard moisture content of 3 per cent as hereinafter described. When so corrected the capacities, which before appeared to vary in an inconsistent manner with grindability, followed an entirely systematic relationship as shown by Figs. 4 and 5.

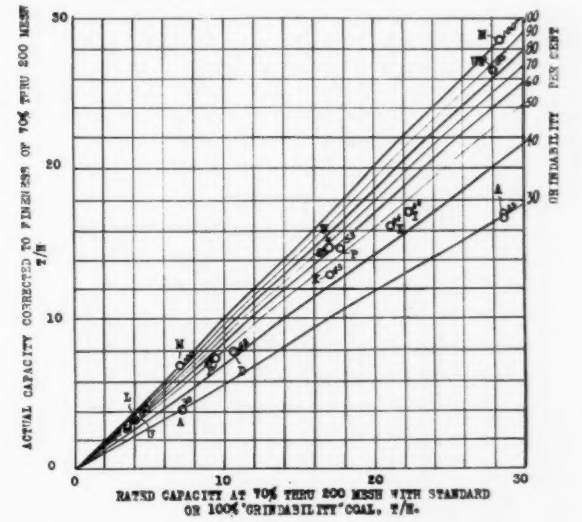
A study of the results obtained with a large number of conical ball mills pulverizing various kinds of coals indicates that the outputs of various pulverizers, tested as shown by Fig. 4, vary systematically with grindability, but, as shown by Fig. 5, are not directly proportional to grindability, increasing at a greater rate. This one would expect on the basis of equations 5 and 6 and Fig. 2.

The relation between grindability and the capacity of pulverizers of an entirely different design, namely a vertical ball mill, is shown by Curve II, Fig. 5, based on data by Cassidy (*4*).

Influence of Fineness of Product on Capacity

The output of a pulverizer is influenced as much by the fineness of the product as by the grindability. Fig. 6 shows the ratio between the output of pulverizers of various types and the output at a fineness of 70 per cent through a 200-mesh screen arbitrarily taken as a standard. This chart summarizes the results of hundreds of tests with various types of pulverizers, most of them made by or under supervision of one of the authors. On studying this figure and comparing it with Fig. 5, it will be found that for a fineness of 80 per cent through a 200-mesh screen the capacity of a pulverizer is about one-half its capacity at a fineness of 50 per cent through 200 mesh, about 60 per cent of its capacity at a fineness of 60 per cent through 200 mesh, and about 80 per cent of its capacity at a fineness of 70 per cent through 200 mesh.

The rate of change of pulverizer capacity with fineness



Mark	Seam or Name	Grindability
A	River anthracite	30–33
L	Kittaning	80–85
D	Nova Scotia	42
K	Kanawaha (Coalburg)	43
I	Illinois	44
P	Pittsburgh	49–53
M	Miller ("B")	95–100
UF	U Freeport	80–85
U	Unknown	61–65

Fig. 4—Effect of grindability on relation between actual and rated capacity of conical ball mills.

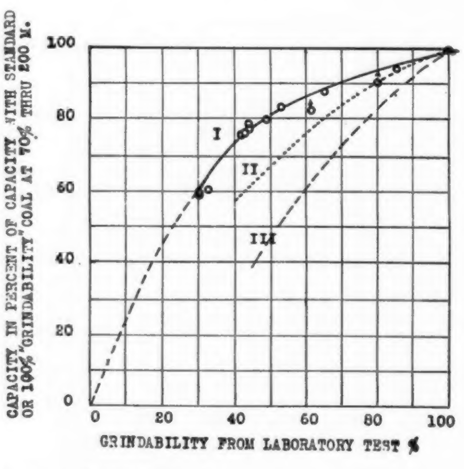
would lead one to suspect that with a given coal the output varies in such a way as to produce an approximately constant amount of surface per unit time irrespective of the fineness. For this to be true it would have to follow that the ratio of the capacity at any stated fineness to the capacity at any other fineness, say for example 70 per cent through 200 mesh, would be the same as the ratio of the surface at that other fineness, (70 per cent through 200 mesh), to the surface at the stated fineness. This conclusion is given some plausibility by the fact that if from Sherman's data shown in Fig. 2 for each of the coals the ratio of the surface at a fineness of 70 per cent through 200 mesh to the surface at every other fineness is computed, the resulting three surface ratio curves a, b and c practically coincide. If this is a coincidence, then it is a still more remarkable coincidence that these surface ratio curves when superimposed on the points plotted on Fig. 6 might be almost said to also represent the most probable curves through the points.

It is difficult to escape the conclusion, therefore, that in order for pulverizer data to be comparable with grindability data, all pulverizer tests must be corrected to the same stated fineness, say for convenience some standard fineness, by multiplying the actual capacity by the ratio of the surface at the stated standard fineness to the surface at the actual fineness. For all practical purposes, values read from the most probable curve through the points on Fig. 6 will be sufficiently accurate if no actual data are available on a particular pulverizer to show the relation between capacity and fineness.

Influence of Feed Size on Capacity

It is customary now to base pulverizer performance predictions on the reservation that the size of feed must not exceed a certain maximum. Primarily this is done to assure uniform feeder performance as well as to prevent irregularities in mill operation which might result from the feeding of excessively large lumps. In certain types of mills large lumps take up valuable space and prevent proper interaction between coal and grinding parts, thereby reducing capacity out of all proportion to the work required to reduce the lumps to proper feed size. In general, it is more economical to reduce large lumps in a crusher than in a pulverizer.

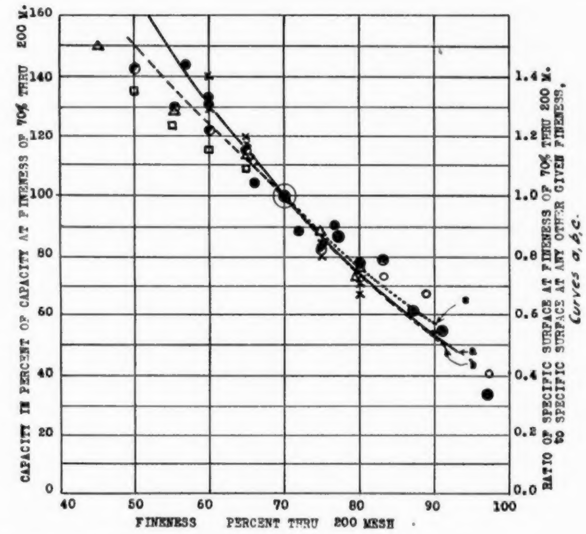
Generally speaking, if the feed is not abnormally large nothing is to be gained by reducing it below the specified size unless the reduction produces a large amount of new particle surface compared to the original surface of feed. Then an increase in pulverizer capacity may be expected which is roughly proportional to the ratio of the new surface produced by precrushing to the total surface of the finished pulverizer product.



I——— Conical ball mills
II...... Vertical ball mills (see text for source of data)
III--- Vertical roller mills

Fig. 5—Relation between grindability by laboratory test and grindability as determined from actual tests in large commercial pulverizers.

One of the writers can call on his own experience to cite increases in pulverizer capacities of 20 to 35 per cent due to precrushing of the feed. A reduction in feed size from 100 per cent through a 1-in. ring to 100 per cent through a $^1/_4$-in. ring



● Large conical ball mill—Illinois coal
◉ Large conical ball mill—Illinois coal
× Large cylindrical ball mill—Indiana coal
○ Large roller mill—Pittsburgh coal
◐ Small 6 roll mill—No. 5 block seam coal
△ Small 5 roll mill—No. 5 block seam coal
□ Small 6 roll mill—No. 5 black seam coal
} points show capacity at given fineness in per cent of capacity at a fineness of 70 per cent through 200 mesh

———a Pocahontas coal
------b Hocking Valley coal
........c Semi-coke
} Curves show ratio of surface at fineness of 70 per cent through 200 mesh to surface at given other fineness. (Small conical ball mill.)

Fig. 6—Relation between fineness and capacity

produced a 20 to 25 per cent increase in the output of each of 4 ball mills whose normal capacity with Pittsburgh coal was 14 tons per hour. A similar reduction in the feed size to a roller mill resulted in a capacity increase of at least 30 per cent, with a much softer coal, however.

Consequently, when comparing pulverizer test results with each other and with grindability data, the pulverizer test results should all be corrected to the standard feed size. This correction is of importance only if the feed is finer than 100 per cent through a $^1/_2$-in. ring and contains large amounts of fines. Slack coals need watching in this respect.

Influence of Moisture on Capacity

The effect of moisture on the output may or may not be quite marked, depending on the pulverizer design. In ball pulverizers arranged for mill drying and employing classifiers which reject a large amount of partially dried oversize in such a manner as to permit it to mix with the wet feed before its entry into the pulverizing zone, the effect of the moisture in the feed on the capacity is small. It is not over 12 to 15 per cent for a total increase in the free moisture of 10 per cent of the weight of the coal.

In ball pulverizers not employing classifiers the reduction in capacity for the same increase in free moisture may be as much as 50 per cent or more. Other pulverizer types may suffer capacity reductions of 15 to 50 per cent depending on the design.

Generally speaking, the relation between capacity and moisture in feed must be known for a given pulverizer in order that test results may be corrected and made comparable with each other and with grindability test results.

Grindability Testing Appraised

Although the definition of grindability as now used is really arbitrary, as shown, and not based on a true conception of the

relation between grindability and pulverizer capacity, the results of grindability tests are nevertheless most useful in estimating pulverizer performance. But it would seem that the value of a grindability test would not be in any way impaired if the results of the test were expressed in a simpler way not involving the calculation of surface factors.

On the basis of a study of the relation between grindability as now used and the percentage through the various screens specified for sieving the product of the grindability testing machine, it would appear that for all practical purposes it would be just as useful to arbitrarily define grindability as the percentage through any one of the screens generally accepted as a standard for that purpose. Fig. 7, showing the relation between grindability as calculated from surface and the screen test results from which they were calculated, indicates that no sacrifice in accuracy would be involved. After all, since the sieving is not carried far enough to give proper weight to the influence of the superfines on the specific particle surface, no additional accuracy is obtained by calculating a so-called specific surface from the screen analysis. But the time required for carrying out and completing a test is materially increased. Considerable time and expense could be saved by screening the grindability machine product through one generally accepted screen and reporting the percentage through that screen as the grindability. Results so obtained in different laboratories could be compared with greater confidence inasmuch as no calculation errors could possibly creep into the reported values. Furthermore, since no grindability test result has any absolute quantitative meaning with respect to any pulverizer except such as can be determined from an empirical relationship derived by parallel tests of stated coals for grindability in the laboratory and in the pulverizer in question nothing is sacrificed by the simplification of the grindability test proposed.

It would seem that a grindability test method in order to have real value should be simple to perform, should require very little time or special apparatus and should be of such a nature that the test conditions could easily be made identical for each sample tested anywhere, any time. All laboratories

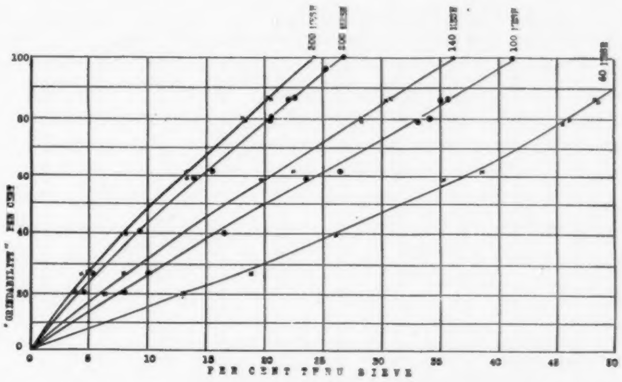


Fig. 7—Relation between calculated grindability based on surface and screen analyses of grindability testing machine product.

adopting such a test method could then reproduce each other's results.

The writers, after testing a large number of samples both in an Abbé jar mill as was done by Cross and in the special grindability machine proposed by Hardgrove, have concluded that if proper care is exercised in preparing the sample and making the test there is little to choose between the two devices and that nothing is to be gained by calculating the so-called surface in preference to using the percentage through say a 200-mesh screen as the "pulverizability" index.

Table I (*5*) shows an entirely distinct grindability scale derived by analyzing the results of tests of more than 40 different Pennsylvania and West Virginia coals in the same roller

TABLE I

Test No.	Seam	State	County	Moisture	Ash	Vol., M.	F. C.	Tons Tested	$\frac{C}{C_s}$
36	"B" or Miller	Penn.	Cambria	2.5	6.9	22.5	70.6	60.3	0.74
28	" " "	"	"	2.2	7.6	28.8	63.6	70.3	0.97
45	" " "	"	"	3.5	8.4	28.7	62.9	75.0	0.52
3	" " "	"	"	2.0	9.9	20.4	69.7	50.9	0.87
10	" " "	"	Clearfield	2.8	11.7	22.2	66.2	77.8	0.74
33	" " "	"	"	2.4	13.1	20.3	66.6	43.6	0.88
14	" " "	"	"	2.8	13.1	19.4	67.5	35.2	0.78
19	" " "	"	"	4.1	13.1	19.4	67.5	101.6	0.95
25	" " "	"	Indiana	2.7	14.3	26.5	59.2	71.4	0.57
53	" " "	"	"	2.0	9.1	23.3	67.6	181.9	0.75
41	" " "	"	Somerset	2.3	8.7	18.9	72.4	55.2	1.00
42	" " "	"	"	4.7	8.7	18.9	72.4	50.2	0.91
27	"E" Vein	"	Indiana	2.2	9.2	29.0	61.8	46.7	0.64
38	Freeport (Lower)	"	Cambria	2.6	9.9	19.9	70.2	45.3	0.72
40	" "	"	"	2.6	9.9	19.9	70.2	60.0	0.64
48	" "	"	"	2.1	9.7	26.1	64.2	90.3	0.76
22	" "	"	Indiana	3.4	9.9	26.4	63.7	160.8	0.82
30	" "	"	Jefferson	2.5	9.3	23.6	67.1	64.2	0.82
24	" Twin	"	Allegheny	1.1	13.1	25.7	61.2	68.3	0.68
47	" (Upper)	"	Cambria	2.0	9.4	28.1	62.5	90.4	0.87
20	" "	"	Clearfield	3.4	12.5	27.5	60.0	120.8	0.72
23	Kittaning (Lower)	"	Cambria	1.8	10.6	28.0	61.4	123.5	0.70
J-9	" "	"	"	1.5	9.8	26.3	63.9	3263.0	0.76
46	" "	"	"	1.6	9.4	19.8	70.8	136.6	0.81
2	" "	"	Clearfield	2.0	12.7	23.4	63.9	68.6	0.91
4	" "	"	"	3.6	10.5	23.5	65.9	75.4	0.62
31	" "	"	"	2.6	9.0	21.9	69.2	113.2	0.71
6	Moshannon	"	Cambria	3.0	10.8	25.0	64.2	98.8	0.79
13	"	"	"	2.8	10.8	26.2	63.0	71.2	0.80
39	"	"	Clearfield	3.1	10.3	21.8	67.9	143.0	0.94
52	Pittsburgh	"	Allegheny	2.7	9.8	34.3	55.9	105.3	0.39
12	"	"	Fayette	3.0	9.2	31.3	59.5	45.1	0.47
29	"	"	Greene	1.2	9.4	33.9	56.7	60.2	0.40
49	"	"	Westmoreland	6.0	9.5	33.7	56.8	83.6	0.49
37	"	"	"	2.9	13.9	27.5	58.6	99.9	0.60
32	"	"	"	1.4	8.6	34.6	56.8	113.1	0.53
1	"	"	"	3.1	8.9	34.0	57.2	123.3	0.65
9	"	"	"	3.2				40.1	0.50
5	"	W. Va.	Marion	2.9	8.9	36.9	54.3	78.3	0.38
7	Sewickley	"	Monongahela and Mingo	2.9	12.8	34.9	52.4	128.7	0.43
34	Seam, State and County unknown			2.1	12.9	27.1	60.0	77.8	0.60
35				2.1	12.9	27.1	60.0	66.2	0.48
26				3.2	8.9	19.3	71.9	55.4	0.82
44				3.1	9.1	21.6	69.5	70.4	0.93
8				3.4				20.1	0.88
51				3.4	10.7	30.8	58.6	188.0	0.41

$\frac{C}{C_s}$ = Ratio between capacity (referred to standard conditions at constant fineness and moisture content at same power input to mill) and capacity with standard coal (Roller Mill).

pulverizer in an eastern utility plant. Each of these tests lasted from 6 hr. to a month and can, therefore, be considered to be quite as accurate as pulverizer tests can be. Unfortunately, these tests were made in 1927 before the value of laboratory grindability testing was appreciated and, therefore, no direct comparison can be made between the true grindabilities as revealed by these actual mill tests and the now tentatively used laboratory grindability scale. But, by comparing the actual grindabilities as revealed by the pulverizer tests with the laboratory tests of those of the coals tested, which are known from subsequent laboratory tests of coals from the same seams and localities, the relation between laboratory grindability and "true grindability" for the pulverizer in question can be safely assumed to be in accord with Curve III, Fig. 5.

As has already been shown by Hardgrove, the volatile content of a coal may be considered as a very rough index of its pulverizing characteristics. Fig. 8 based on the roller mill results tabulated in Table I shows a similar approximate relationship between volatile and grindability, and Fig. 9 also shows such a relationship between fixed carbon and grindability. However, the relationships are too vague to warrant the use of either volatile or fixed carbon content as a basis for exact prediction of pulverizing characteristics.

Conclusions

(1) Grindability test data and actual test results of a stated pulverizer can be reconciled only if reduced to a common basis by referring all data to standard conditions because

(*a*) Variations in fineness may affect the tonnage output as much or more than variations in grindability.

(*b*) Variations in moisture content and feed size may have sufficiently large effects to mask the effects of variations in grindability.

(*c*) Variations in the method of loading a given pulverizer may cause variations in output and fineness sufficient to mask the effect of variations in grindability. Therefore, since variations in loading are generally revealed by variations in power input at the pulverizer shaft, all test data of a given pulverizer should be corrected to the same power input to the pulverizer shaft in order to be comparable.

(2) Grindability when defined as proportional to the surface per pound of a given coal to the surface per pound of a standard coal after identical standardized treatments in a standard laboratory mill is an arbitrary factor, which by itself has no theoretical relation to the ratio between the capacity obtainable with a given coal and the standard coal when pulverized

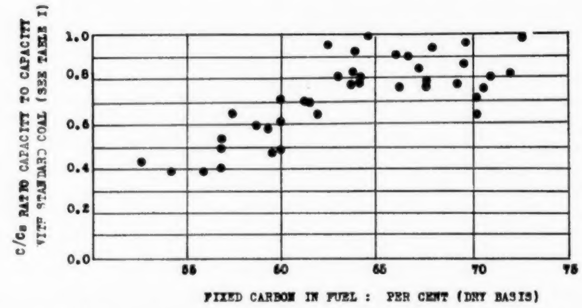


Fig. 9—Relation between capacity (standard conditions) and capacity with standard coal (roller mill).

to the same fineness. In order that the results of a laboratory grindability test may directly measure the theoretical relation between the capacity obtainable with a given coal and the standard coal when pulverized to the same fineness the ratio of the surface obtained in the grindability test to the surface obtained with a standard coal similarly treated must be multiplied by the ratio between the surface per pound of the given coal and the surface per pound of the standard coal at the same fineness. For the surface per pound at a given fineness is not the same for all coals, as would have to be assumed in order that grindability as heretofore defined be directly proportional to mill capacity with various coals.

(3) Since grindability as commonly defined as the ratio of the surface per pound of coal to the surface per pound of a standard coal when similarly treated in a grindability machine is arbitrary and involves the calculation of a theoretical surface on the basis of screen data which do not go far enough into the superfine range to truly differentiate between the hard and soft coals, it would be just as satisfactory for the purpose of establishing an arbitrary yardstick by which to measure the relative softness of coals to use the fineness through one generally accepted screen as the index number. Since an empirical relation has to be established anyway between any laboratory grindability test result or index number and the relative capacity of various pulverizers with coals of various index numbers, nothing would be sacrificed by the simplification of the grindability test and definition as suggested.

(4) Although the volatile content or the fixed carbon content of a coal may be used as a rough index of its relative softness, no sufficiently accurate relation has yet been revealed between these or any other properties of a coal, which can be established by chemical analysis, and the softness to take the place of some grindability test.

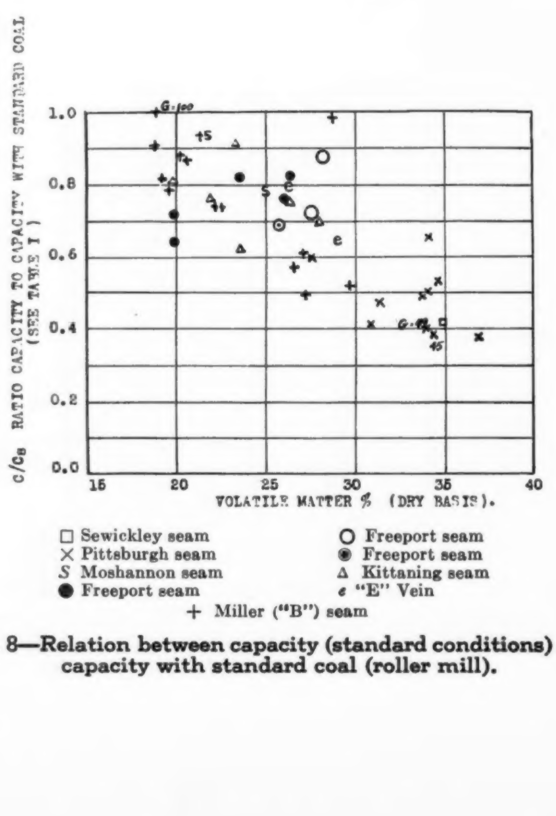


Fig. 8—Relation between capacity (standard conditions) and capacity with standard coal (roller mill).

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(5) Based on Private Communication, courtesy of Mr. James A. Powell, Vice President, W. S. Barstow & Co., Inc.

The Northern Equipment Co., Erie, Pa., manufacturers of Copes Feed Water Regulators, Differential Valves, Pump Governors and allied equipment, announce the appointment of C. H. Wilson, 1403 Park Boulevard, Troy, N. Y., as sales representative in the Albany district.

The Measurement and Properties of Cinders and Fly-Ash

By ARTHUR C. STERN[1]

This paper presents the results of a two-year investigation by the Smoke Abatement Research Department of Stevens Institute of Technology. Part I of the paper describes the study of different test methods which are broadly classified under the headings: filtration, centrifugal separation, electric precipitation and impingers. The cyclone was finally selected from the high sample rate methods as best meeting the requirements of practical power plant testing. Experiments with model cyclones led to the development of a design of cyclone for use in actual boiler tests. Part II describes tests of five boilers in three plants. The primary object of these tests was to test the test method rather than the plants. Part III is devoted to study of and comment on the test results.

Introduction

IT IS IMPOSSIBLE to set logical legal limits of maximum permissible cinder and fly-ash emission from power plant stacks until, first, a standard measurement method for measuring the emission has been agreed upon and, second, until sufficient test data have been assembled using that standard measurement method to allow reasonably good judgment in setting the maximum permissible value. Therefore, when it was suggested that such a maximum permissible emission regulation be instituted in New York City, the Smoke Abatement Research Department of Stevens Institute deemed it an expedient time to start what developed into a two-year study of available measurement methods in the hope that a standard test method could be evolved and that sufficient representative test data could be assembled to yield a true picture of the situation. Fortunately, the measurement methods so developed have yielded much more data than was originally anticipated. It has proved possible to collect large enough samples, first, to allow a study of the properties of the particles themselves, yielding data which will be useful for the rational design of separators of cinders and fly-ash from flue gas, and, second, to allow the computation of "the per cent of the heating value of the coal fired lost in the cinders or fly-ash," which, in general, will cause a considerable decrease in the "Radiation and Unaccounted For Loss" as usually reported in the boiler heat balance.

Undoubtedly, numerous power plant designers and operators have seen fit to make similar studies of their own cinder and fly-ash problems. There must be a large amount of valuable data hidden away in their files on measurement methods and the results of measurements of dust loadings and properties. However, very little of it has ever been made public so that others could benefit by their pioneer work. Possibly the reason is that most of the work in this field heretofore has been with respect to the design and acceptance testing of dust separators, which results are not always made public. However, it is hoped that the discussion of this paper will not only bring to light some of these data but will also consider the possibility of using the test methods to be described as standards for dust separator acceptance tests.

PART I

Methods for Measuring Dust Loading in Flue Gas

Study of Test Methods. The first part of the Stevens research program consisted of actual trials of a number of possible test methods under power plant conditions. The test methods selected for trial were those which had been previously used successfully for the measurement of atmospheric dusts (*1*),* dust in blast furnace gas (*2*), lampblack in gas (*3, 4*), soot in smoke (*5, 6*), in addition to those previously used for the measurement of cinders and fly ash (*7, 8, 9, 10, 11, 12, 13, 14, 15, 16*). The methods tested may be classified according to type:

(*A*) Filtration through cotton, woolen and asbestos bags of various sizes and shapes; through paper and alundum thimbles; through beds of granulated and pulverized sugar of various depths; and through asbestos wool.

(*B*) Centrifugal separation in cyclone collectors of various sizes and proportions.

(*C*) Electrical precipitation in precipitators of various dimensions using various potentials.

(*D*) The Greenburg and Smith type of impinger (Fig. 1).

These methods should be again classified from the point of view of the flue gas sampling rate into the following groups:

(*E*) Those in which the sampling rate is limited to the range of 5 cu. ft. of gas per min. and below by the rapid increase in pressure drop through the device when the sampling rate is increased; the thimbles, sugar tubes, asbestos filters and impingers.

(*F*) Those in which a high sampling rate is permissible; the bag filters, electric precipitators and cyclones.

Test Methods Having Low Sampling Rate. Tests of the methods in group (*E*) (low sampling rate) quickly showed that the sugar tubes and asbestos filters were inferior to the other two methods. In the author's opinion, the impinger is a preferable test method to either the paper or the alundum thimble methods, for the following reasons:

Paper thimbles are hygroscopic, hence they require a prolonged drying before and after use and an expert weighing technique. They char and become brittle when subjected to

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* Numbers in parentheses refer to bibliography at end of article.

too high a flue gas or drying oven temperature, or to the acid condensation caused by too low a flue gas temperature. They clog up rapidly when in use, making it difficult to maintain a constant sampling rate. It is difficult to reclaim the sample from them for subsequent analysis and is impossible to use them a second time since they must be discarded after each test.

The preparation time and degree of expert technique necessary with alundum thimbles is considerably less than that required for paper thimbles because, before use, the thimble may be heated to red heat, cooled and weighed, saving the preliminary drying time. Alundum thimbles, also, do not char or become brittle and may be used for several repeated tests by burning out the previous deposit from the inner walls of the thimble. However, to offset these advantages, they have an initial pressure drop several times higher than paper thimbles at the same rate of gas flow necessitating sampling rates lower than those using paper thimbles. They also clog up rapidly when in use, making it difficult to maintain a constant sampling rate, and, also, the samples from them may not be reclaimed for subsequent analysis. The facts ascertained concerning alundum filters most likely are also applicable to porous glass filters which were not tested.

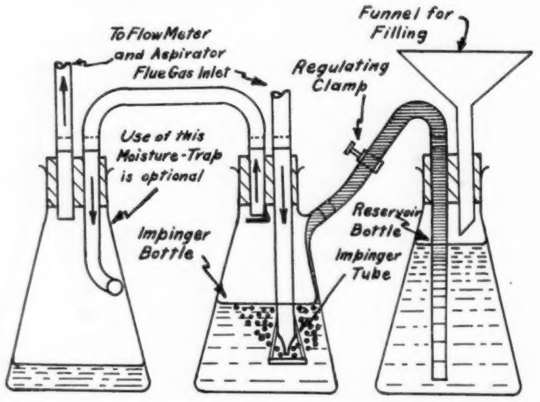


Fig. 1—Impinger adapted for use with flue gas.

The maximum efficiency of collection of incoming dust obtainable with impingers is as high as with either of the thimbles, and for all three methods approaches 100 per cent. Impingers may be so designed that this range of maximum efficiency may occur at any reasonable low sampling rate. The ones commonly used have their maximum efficiency at about 1 cu. ft. of gas per min., but it is also possible to build impingers for 5 cu. ft. per min. or higher. Impingers must be used at close to their designed sampling rate. At lower sampling rates, their efficiency falls off; at higher sampling rates, the pressure drop through the device is much greater. When used at its proper sampling rate, the efficiency remains constant throughout a test run and the pressure drop does not increase, thus permitting tests of long duration at constant sampling rate. It takes but a few minutes to prepare an impinger for use. After use, the handling of the sample is a matter of simple laboratory technique.

A complete sample is reclaimed available for subsequent chemical or physical analysis. The same impinger may be used for any number of tests in rapid succession. It is necessary, however, to take special precautions to eliminate the rapid rate of loss by evaporation of the liquid in the impinger into the hot flue gas being sampled. This may be done most conveniently as shown in Fig. 1. By means of this arrangement, the pressure drop across the impinger is high enough to draw fresh distilled water from the reservoir bottle *A* into the impinger bottle *B* so that the level in the impinger may be maintained constant in spite of evaporation. One advantage possessed by impingers, and not by any of the other methods tested in both the low and high sampling rate groups, is that by using the proper water solutions (*7*, *17*) in the impinger instead

TABLE I—TESTS OF EFFICIENCY OF CYCLONE DUST COLLECTOR BY MEANS OF ELECTRIC PRECIPITATOR

Test No.	Test Duration, Minutes Cyclone	Test Duration, Minutes Precipitator	Cyclone Collection, Grams	Precipitator Collection Corrected to 100% Eff., Grams	Cyclone Flow c.f.m. at 60° 30″	Precipitator Flow c.f.m. at 60° 30″	Material Leaving Cyclone Uncollected, Grams	Efficiency %
1	10:00	8:55	73.1	0.325	470	102.0	1.7	98.2
2	10:00	9:30	128.0	0.570	477	90.7	3.0	97.5
3	10:00	9:30	89.1	0.335	466	57.9	2.8	97.2
4	10:00	9:30	85.5	0.285	470	56.2	2.5	97.5

of distilled water, it is possible to measure SO_2 and SO_3 concentrations in the flue gas being sampled at the same time that a dust sample is being collected. It also should be noted that the impinger is recognized as the standard method for measuring atmospheric dust (*18*).

Test Methods Having High Sampling Rate. Tests of the sampling methods of group (*F*) (high sampling rate) were more exhaustive than the low sampling rate group because the ideal sampling method should have a high sampling rate in order to allow the withdrawal of representative samples from the flue gas stream. All the methods tested in the low sampling rate group were high collection efficiency, high pressure drop methods. The situation is more complex in the high sampling rate group.

The efficiency of a cyclone collector of given dimensions increases with sampling rate until a maximum, which may be over 98 per cent for a properly designed cyclone, is reached. At low sampling rates, its efficiency may be only 50 or 60 per cent. The pressure drop through a cyclone collector increases as the square of the sampling rate. The relation between dimensions, efficiency and pressure drop in cyclones will be discussed in detail later in this paper. The pressure drop at any sampling rate is lower than any method tested other than the electric precipitator. At constant sampling rate, the pressure drop remains constant throughout the duration of a test run. Practically no preliminary or subsequent preparation time is necessary to prepare the cyclone for use or repeated use. The cyclone sample is collected dry, ready for immediate weighing and chemical or physical analysis. If the temperature of the flue gas in the cyclone is below its dew-point, moisture on the walls of the cyclone makes proper collection difficult, therefore cyclones must always be insulated. There is no upper temperature limitation.

Bag filters of several different sizes, fabrics and shapes were tested. None of these factors had any apparent effect upon the collection efficiency which was high in all cases, approaching 100 per cent, nor could much effect of these factors upon pressure drop be discovered. The pressure drop through the bags increased as the square of the sampling rate and was about three times that of a cyclone built to handle the same gas flow. The bags tend to clog up gradually and must be shaken free from time to time to maintain reasonably constant conditions over a period of time. To avoid charring the fabric, cotton bags must not be used above 200 fahr., nor woolen bags above 250 fahr. The lower temperature limit for these bags is set by the dew-point of the flue gas. At temperatures above and below these limits, asbestos bags must be used. Handling bag filters to obtain accurate weighings is difficult; in fact, the author found no really satisfactory method of either obtaining accurate gross and tare weights of large filter bags or of removing the sample from the bag for independent weighing. The nearest approach to a satisfactory bag filter technique consists in the use of the type recommended by Jacobus and Bailey (*11*) in which the bottom of the bag is not sewn together, but is joined to the top of a glass beaker. Under this arrangement the bulk of the dust falls into the beaker which may be removed for weighing. If bags are cleaned after each test, they may be reused repeatedly.

Electric precipitator tubes have the lowest possible pressure drop at any given gas flow. The efficiency of a two or three section tube, designed in the manner which will be described

later in this paper, is not necessarily 100 per cent, but even if the efficiency is below 100 per cent the actual efficiency may be calculated in a manner to be described, so that the weight of collected dust divided by the calculated efficiency will yield a figure equal to 100 per cent of the entering dust. Tubes may be designed to handle almost any sampling rate within reason. The pressure drop does not increase during the course of a test run so that tests of long duration at constant sampling rate are possible. It is possible to measure accurately by this method dust concentrations so low as to yield dust samples weighing less than the weighing error of a bag or paper filter. All of the sample from an electric precipitator tube may be reclaimed for subsequent chemical or physical analysis. The tubes require very little time for preparation or subsequent handling and may be used repeatedly. There are several major drawbacks to the use of precipitators. They require a source of high potential alternating current. They must be carefully watched while in use because any one of a number of things may go wrong during a test run. Where the dust being measured contains some especially heavy cinder particles, it is usually desirable to remove them in a cyclone before they enter the precipitator or they are liable to be blown through the precipitator by virtue of their size and inertia.

Choice of Most Useful Test Methods. A comparison of the three high sampling rate methods led to the selection of the cyclone method as being the most useful for all-around test work. In use, its collection efficiency may be somewhat below that of the bag filter or the calculated results from an electric precipitator, but the many advantages of this method more than compensate for the small efficiency loss. The choice of the cyclone in preference to the bag filter method was made with the knowledge that if a high efficiency method was needed for check purposes or the measurement of very low dust concentrations, either the impinger or the electric precipitator could be used. Subsequent experience in three power plants has proved that the choice was sound. Cyclone collectors have yielded satisfactory measurements on boilers fired by underfeed stokers, chain grate stokers and pulverized coal in all cases. In the case of stokers at very low boiler ratings and outlet concentration measurements of dust separators, the dust loadings are so low as to indicate that, although the cyclone, of the type used

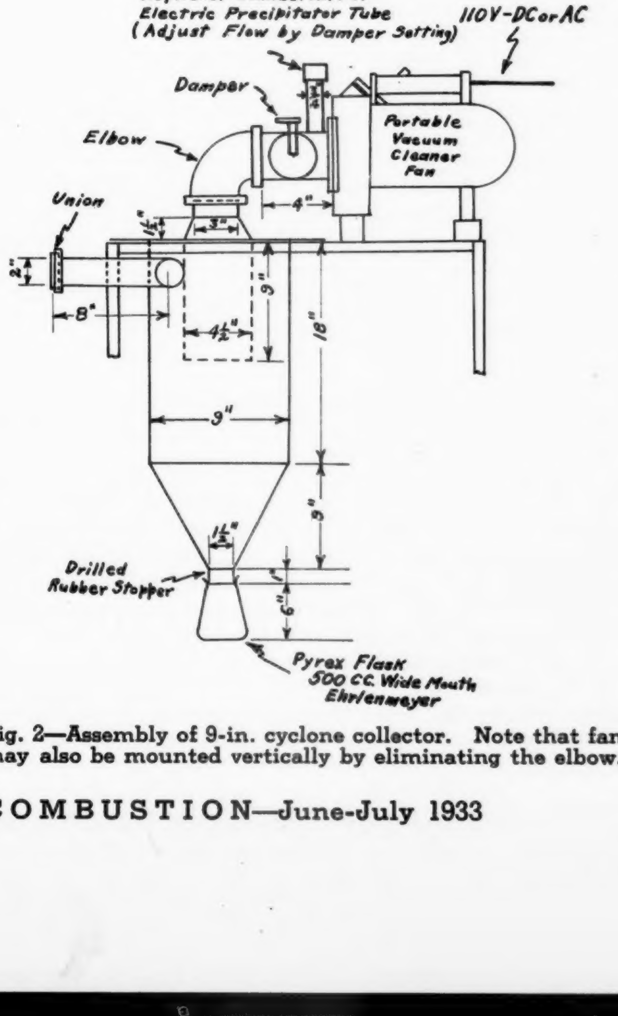


Fig. 2—Assembly of 9-in. cyclone collector. Note that fan may also be mounted vertically by eliminating the elbow.

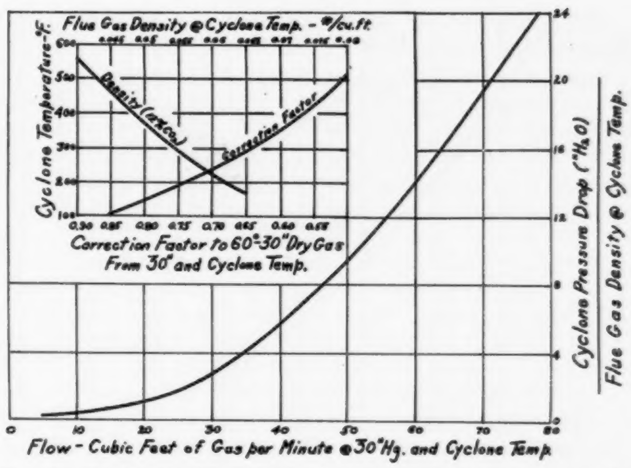


Fig. 3—Typical calibration curve and auxiliary curves for calculating flue gas flow through 9-in. cyclone collector.

for inlet concentration measurements, renders satisfactory results, greater accuracy may be obtained by using electric precipitators, impingers or cyclones of smaller diameter than those used for inlet concentration measurements. It should be particularly noted that the only cases where the larger cyclone is not unqualifiedly recommended are cases where the bag filters and thimble filters would have been equally unsatisfactory, and where, because of the absence of heavy cinder particles or of undue gas stratification due to high gas velocity, either the electric precipitator used alone or the impinger sampling flue gas at a relatively low rate could be used to best advantage. It should also be noted that it is only on rare occasions that there is any necessity for measuring cinder and fly-ash carry-over at low boiler ratings. The usual conditions that cause measurements to be made are those of high boiler rating and heavy dust concentration, which conditions are satisfactorily met by the use of a cyclone.

Four tests were run to determine the efficiency of a cyclone (of dimensions to be described later) when sampling the uptake of a boiler burning pulverized coal. About one-eighth of the gas leaving the cyclone was caused to flow through our electric precipitator so that the dust loading of the cyclone exhaust could be measured. The results (Table I) not only show that the cyclone efficiency was over 97 per cent in all cases, but that the electric precipitator can be used to measure the low dust concentrations existing in the cyclone exhaust.

Design and Operation of Cyclone Collector. Previous investigators in this field who have used true cyclones, or separators of the centrifugal type, have all deemed it necessary to guard against the possibility of dust leaving the collector uncollected by using a subsequent filter paper (*8*), paper thimble (*7*), alundum filter (*15*), wire gauze screen (*9*), or some other type of filter bed (*13*, *14*). With the exception of the wire gauze screen, the effect of the filter medium is to greatly decrease the gas flow through the device at a given pressure drop and, conversely, to necessitate a much higher pressure drop to maintain high enough gas flows to cause centrifugal collection. If it is desirable to measure the dust in the gases leaving the cyclone, it can be done by passing it through an electric precipitator tube which will not appreciably reduce the gas flow rate through the cyclone where as high a flow as possible is desired in order to attain high cyclone efficiency. However, in a properly designed cyclone, even this expedient is unnecessary because the efficiency of the cyclone used alone is high enough for all practical purposes. Two big advantages gained by eliminating the subsequent filter is that instead of requiring a vacuum pump or steam aspirator to pull the flue gas through the device and of having the sampling rate gradually decrease as the filter clogs up, the cyclone may now be run for any length of time at constant sampling rate by means of a small portable vacuum cleaner fan or similar source of low vacuum.

The dimensions of the cyclone collector developed as a result of these investigations was evolved by first studying a series of glass cyclone models of various shapes, sizes and dimensions and noting the effect of changes upon the streamlines in the cyclone. As a result of this study of glass models, dimensions for the first of a series of three metal cyclones were determined. In the second and third metal cyclones, the faults discovered in the previous cyclones were corrected so that the present cyclone offers the best possible compromise between efficiency, ease of operation and ease of construction.

The dimensions of the most recent of these cyclones which was built to be used with a portable vacuum cleaner fan is shown in Fig. 2. As has been previously noted, for use with low dust concentrations, a smaller diameter cyclone, having all its dimensions proportionately reduced from those shown in Fig. 2, may be used. This cyclone is of welded construction using 2-in. pipe for the tangential inlet and 3-in. pipe for the axial outlet connection. The following facts are of particular interest. This cyclone is used without an external flow meter to measure the gas flow. Static pressure taps of $^1/_4$-in. pipe are inserted in the inlet and outlet pipes. The pressure drop measured between these two pressure taps has been calibrated in terms of gas flow by means of a standard wooden flow nozzle. Such a calibration curve is shown in Fig. 3, together with the two auxiliary curves necessary to use the calibration at any given cyclone temperature. (Cyclone temperature means the temperature of the gases in the cyclone as contrasted with the true flue gas temperature.) The auxiliary curve labeled "correction factor" may be used for converting values of gas flow from dry flue gas at 60 fahr.–30-in. Hg to the condition of wet flue gas at 30-in. Hg and the given temperature, as well as vice versa. This last curve is, of course, different for each type of fuel, being particularly susceptible to changes in moisture and volatile matter. The auxiliary curve labeled "Flue Gas Density" differs for different CO_2 contents, as well as different temperatures. When flue gas samples are drawn into this cyclone through an 8-ft. length of 2-in. pipe using different sized sampling tips, made of standard pipe nipples and pipe reducers, the rates of flow that may be maintained at various angles of damper opening are shown in Table II expressed as cubic feet of dry flue gas per minute at 60 fahr.–30-in. Hg.

The method of using this cyclone for test runs is as follows:

1. Before a test run, a preheating run of about five minutes is necessary to heat up the apparatus to higher than the dew-point. A spare Erlenmeyer flask (500 cc. wide mouth) is used for this preheating run. During the preheating run, the flask to be used during the test run is preheated in the stream of hot exhaust gas from the fan. All adjustments of dampers, etc., should be made during the preheating run.

2. At the end of the preheating run, the fan is stopped, the spare flask is replaced by the clean preheated flask, the fan is again started simultaneously with the starting of the stopwatch and the test run begins. An alternative method of starting a test run is to switch flasks while the fan is running, simultaneously starting the stopwatch. This latter method is also useful when one test is to immediately succeed another, without an intermediate preheating run.

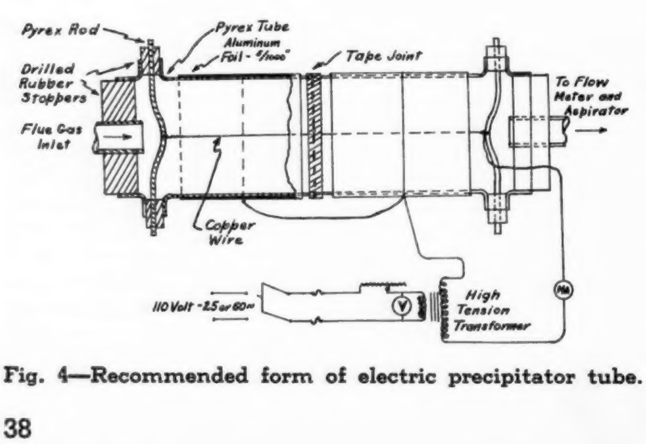


Fig. 4—Recommended form of electric precipitator tube.

3. Readings at about 2-min. intervals are made of cyclone temperature (by means of a 500-fahr. mercurial thermometer inserted into the cyclone through a drilled rubber stopper) and of cyclone pressure drop (by means of a 2-in. inclined tube draft gage connected across the inlet and outlet static pressure taps). Readings should also be taken during the course of the test run, of room temperature, flue gas temperature and draft.

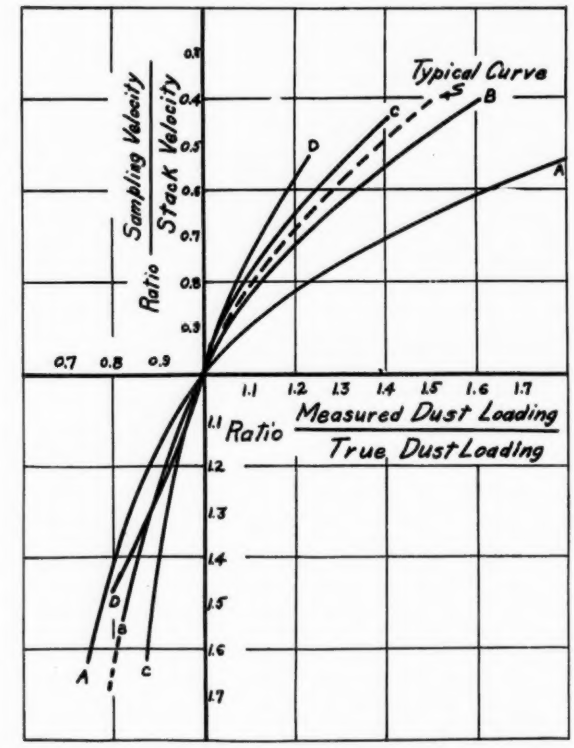


Fig. 5—Correction curves for improper velocity ratios. Source of curves (bibliography references) A—(23); B—(8); C—(24); D—(9).

4. The duration of a test run depends mainly upon the size of the visible collection in the Erlenmeyer flask. When a sufficient quantity has been collected for the type of analysis desired, the run may be stopped. Unless this condition indicates otherwise, the following test durations will yield sufficient sample for the usual analysis: pulverized coal—10 min.; stokers at high boiler rating—20 min.; stokers at low rating—30 min. It is, of course, obvious that furnace conditions must control test duration to the extent that they must be constant and representative during the whole test run.

5. It is not advisable to change boiler rating during a test run. Rather make two or more separate test runs, one for each boiler rating, unless the change-over conditions are being specifically studied.

6. The normal type of test run is one during which the sampling tube and tip are spotted at a known point in the flue gas stream and remain there for the entire run. For this condition and that of a constant boiler rating during the run, the damper requires no adjustment during the test run. To traverse a flue gas stream, it is preferable to take several such spot samples at several known points in the cross-section of the stream rather than to attempt to obtain a single test run during which flue gas is withdrawn from a number of different spots in the cross-section.

7. The test run may be stopped by simultaneously stopping the fan and closing the damper and then carefully removing the flask so that none of the contents are lost in the gas that will start to flow in or out of the cyclone bottom depending upon the draft.

TABLE II—FLUE GAS SAMPLING RATES IN C.F.M. DRY FLUE GAS AT 60°-30" USING CYCLONE COLLECTOR

Damper Opening	Sampling Tip Size 1"	1¼"	1½"	2"
Full—90°	31.7	42.7	47.0	51.2
67½°	30.3	41.7	43.6	48.6
45°	28.8	37.7	39.0	42.7
22½°	25.0	28.0	30.5	30.1

8. The contents of the flask are weighed to 0.1 gram accuracy: This may be done directly in the flask by subsequently running a tare weight on the flask. It is possible to use a small portable balance for this weighing. The contents of the flask are then ready for subsequent sieving or chemical analysis.

9. The 2-min. readings of cyclone temperature and cyclone pressure drop are averaged, the flue gas density corresponding to the average cyclone temperature is read from curves similar to one of the auxiliary curves of Fig. 3, the average cyclone pressure drop is divided by this average flue gas density, and the flue gas flow rate in cubic feet per minute at cyclone temperature corresponding to this quotient is read from the main curve of Fig. 3. This value of gas flow rate is corrected to standard conditions of cubic feet of dry flue gas per minute at 60 fahr. and 30 in. Hg by means of the "correction factor" obtained from a curve similar to one of the auxiliary curves of Fig. 3.

10. The net weight of the collected dust sample divided by the corrected gas flow rate, times the test duration in minutes, is equal to the dust loading in grams per cubic foot of dry flue gas at 60 fahr. and 30 in. Hg.

At this point, it is well to note that only by making the cyclone of a corrosion- and rust-resistant metal, such as 24-12 or 18-8 chrome-nickel steel, can the results continue to be relied upon after the metal has been subjected for a while to flue gas or, even, to normal outdoor atmospheric conditions.

The Design and Operation of Electric Precipitator Tubes. The theory of electrical precipitation has been discussed and experimentally verified by Simon and Kron (*19*) who show that the efficiency of precipitation in a cylinder of length D with gas at velocity V is

$$\text{Efficiency of collection} = 1 - e^{-\left(\frac{KD}{V}\right)}$$

where e is the naperian base and K is an experimental constant.

This equation states that the efficiency is independent of the concentration of the entering dust; is proportional to the length of time the gas remains in the precipitator and is the same for each equal element of length of the precipitator. This last fact may be further interpreted to state that the ratio of the dust precipitated in any unit length to the dust precipitated in the following equal unit length must be a constant, and that this constant must be a measure of the efficiency. Stated mathematically, the resulting relation between the weight (W′) of precipitate in a unit length (u); the weight (W″) of precipitate in the following equal unit length (u); the total length of precipitator (D) and the fraction of the entering dust leaving the precipitator unprecipitated (F), is:

$$F = \left(\frac{W''}{W'}\right)^{\left(\frac{D}{u}\right)}$$

which in the case of a precipitator having two equal halves becomes the very simple relationship

$$\text{Efficiency of precipitation} = 1 - F = 1 - \left(\frac{W''}{W'}\right)^2$$

Thus, from a theoretical basis, it seems possible to use multisection precipitators and to calculate the efficiency from ratios of weights precipitated in those sections. Teletov (*16*) checked these theoretical results experimentally on flue gas dust loadings using direct current and concluded that actual precipitation is close enough to being exponential with length of tube to allow the use of this type of calculation. Use of two- and three-section precipitators using alternating current in the Stevens investigations has confirmed the usefulness of this procedure.

The use of the $\left(\frac{W''}{W'}\right)$ ratio in a two-section precipitator has two advantages; it allows the calculation of precipitator efficiency, and it serves as a guide to indicate whether or not the conditions during a test run were satisfactory, since it is wise to set a maximum value of the ratio beyond which all test runs are rejected. Too high a value for the ratio indicates either that no corona was on the wire during the run or that the velocity through the tube was too high.

Although the tubes used during this investigation were developed largely by a "cut and try" process starting from the basic designs for alternating current used successfully by Drinker (*20*), an attempt has been made to rationalize the design of a tube by using the experimentally and theoretically correct assumption that the optimum conditions for precipitation occur when there is a corona on the axial wire. Peek's

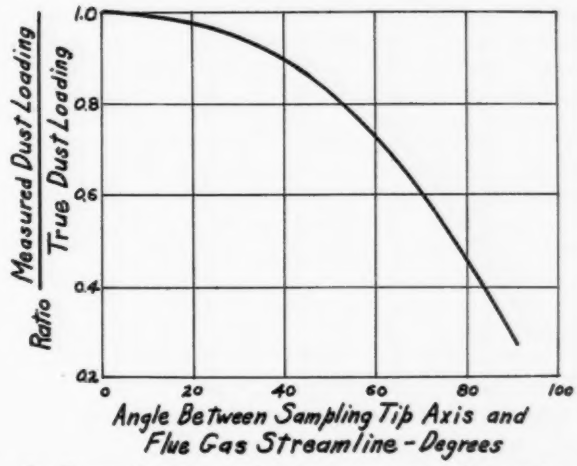


Fig. 6—Correction curve for improper sampling tube position, bibliography—(8).

book, "Dielectric Phenomena in High Voltage Engineering" (*21*), contains considerable data concerning the conditions necessary to maintain concentric cylinders in a state of corona for both alternating and direct current. By using some of his data directly, and recalculating other of his data, the following are arrived at as the limiting conditions (*a*) for corona to first appear and (*b*) corona to change to spark-over conditions; both for frequencies below 100 cycles:

$$(a)\ E_{\text{Start of Corona}} = 318\left(1 + \frac{0.308}{\sqrt{dr}}\right) r \log_e \left(\frac{R}{r}\right)$$

$$(b)\ E_{\text{Start of Spark-over}} = 318\left(0.37 + \frac{0.124}{\sqrt{d}}\frac{R}{r}\right) r \log_e \left(\frac{R}{r}\right)$$

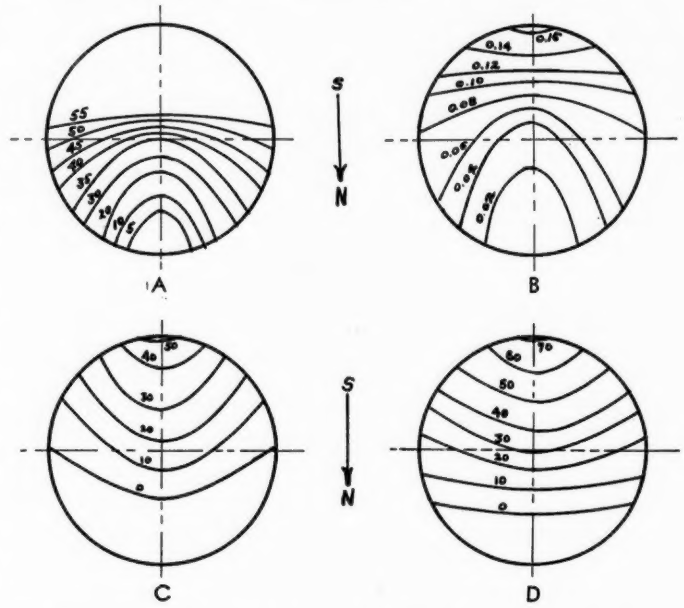
where E = impressed voltage—peak kilovolts
R = radius of outer cylinder
r = radius of inner cylinder or wire
d = relative density of the gas to air at NTP

Of these factors, E, R and r are controllable by design, as is a fourth factor, v, the velocity of the gas through the tube. The velocity is limited by the fact that it is desirable in a two-section precipitator to have 80 per cent or more of the total precipitate occur in the first section. In an a.c. precipitator having a sectional tube length under one foot this may be obtained only by the use of relatively low gas velocities of the order of 10 ft. per sec. or less. Another factor limiting gas velocity is the fact that high velocity gas tends to sweep heavy particles from the point where they originally precipitate to points farther along the tube or out of the tube entirely. As has been indicated previously, this difficulty may be overcome by using a cyclone collector ahead of the precipitator to collect the heavy

cinders. If this is not done, velocities below 5 ft. per sec. must be used. In general, it is best to choose a gas velocity as low as is consistent with other operating factors. Good results have been obtained using values of R from $^3/_4$ in. to $1^1/_2$ in. Values of r have been satisfied by wire sizes of from No. 20 to No. 30 B. and S. gage. The source of impressed voltage, E, has been two 25-cycle General Electric luminous tube transformers either connected in series to yield a maximum peak voltage of about 40 kv. or used separately to yield maximum peak voltages of half that amount. Resistances in the primary circuits of these transformers allow the voltage to be maintained at values below the maximum. An a.c. microammeter in the secondary circuit indicates whether or not corona conditions are being maintained. A satisfactory design of tube subject to the foregoing considerations is shown in Fig. 4.

The direct application of a.c. to the tubes considerably simplifies operation by eliminating the rectifier. Theoretical considerations applicable to d.c. tubes also apply to a.c. tubes. Ionization occurs in similar manner, but precipitation depends much more upon the so-called "electrical wind" than upon the normal electrostatic field forces. The "electrical wind" which occurs with equal intensity in a.c. and d.c. tubes, is the effect occurring when the field about the wire is so intense that all ions drawn to the wire are caused to approach it at such a high velocity that they produce new ions in the vicinity of the wire by collision with the gas or electrode molecules. These new ions of the same sign as the wire will be repelled with great velocity toward the cylinder. This flow of repelled ions constitutes the "wind" and acts almost from the surface of the wire radially in all directions. In general, a.c. precipitation requires lower gas velocities than d.c. precipitation, due to the somewhat lower efficiency and the tendency of the heavier particles of the precipitate to "dance" on the surface of the tube. The agglomerating action of a.c. upon small particles to form flocculated groups is, however, particularly valuable in effecting their collection.

In operation, flue gas is drawn through the tubes by means of fans or aspirators and is measured by orifice meters or displacement meters. Test runs may vary from 10 min. to an hour, depending upon dust loading and sampling rate. Flue gas temperatures in the tubes should be above the dew-point to obviate spark-over due to moisture.



(A) Lines of constant velocity in feet per second.
(B) Lines of constant dust loading in grams per cubic foot of dry flue gas at 60 fahr. and 30 in. Hg.
(C) Lines of constant per cent by weight of particles greater than 150 microns.
(D) Lines of constant per cent by weight of particles greater than 75 microns.

Fig. 7—Traverses of east uptake, Boiler A, 40 lb. of coal per sq. ft. of grate area per hr.

Sampling Errors and Corrections. There are sources of error in measuring cinders and fly-ash quite independent of the collection efficiency of the test method employed. These ex-

TABLE III—DATA DESCRIBING BOILERS TESTED

Boiler	A	B	C	D	E
Company	Interborough Rapid Transit	New York Steam Corp.	New York Steam Corp.	New York Steam Corp.	New York Steam Corp.
Plant	59th Street	Kips Bay	Kips Bay	Burling Slip	Burling Slip
Boiler	No. 57 also (Nos. 14, 16 and 18)	No. 3	No. 4	No. 5	No. 13
Type of Firing	Underfeed Stoker	Vertically Fired	Tangentially Fired	Chain Grate Stoker	Chain Grate Stoker
Type of Fuel	Semi-Bituminous	Bituminous	Bituminous	Anthracite	Coke
Size of Fuel	Run of Mine	Pulverized	Pulverized	Screenings	Breeze
Coal—Fineness	On 1″ —15.3% On $^1/_2$″—12.1% On $^1/_4$″—15.7% Through $^1/_4$″—56.9%	On 200 mesh—17.8%, through 200 on 325—20.9%, through 325—61.3%	On 200 mesh—17.8%, through 200 on 325—20.9%, through 325—61.3%	No. 1 Buck— 2.0% No. 2 Buck—13.8% No. 3 Buck—71.4% Dust—12.8%	No. 1 Buck— 9.3% No. 2 Buck—17.4% No. 3 Buck—26.7% Dust—46.6%
Firing Equipment	Taylor	Lopulco Storage System	Lopulco Storage System	Coxe Forced Draft	Coxe Forced Draft
Size of Stoker (sq. ft.)	110 7 retorts 17 tuyeres	......	......	262 (on 2 stokers)	448 (on 2 stokers)
Number of Burners	......	12 (6 in each half)	12 (3 in each corner)	......	......
Coal Analysis, % Volatile	17.3	35	35	7.2	1.8
Coal Analysis, % Ash	7.1	8.7	7.8	11.7	11.9
Coal Analysis, % Moisture	2.7	4.0	4.0	8.6	10.0
Ash Fusion Temp. (fahr.)	2,770	2,250	2,250	2,500	2,650
Furnace Volume (cu. ft.)	700	19,000	19,000	1,700	3,800
Size of Boiler (sq. ft. of h. s.)	6,000	20,500	20,900	10,000	18,600
Size of Economizer (sq. ft. of h. s.)	......	10,080	10,080	7,250	8,640
Size of Superheater (sq. ft.)	1,700	......	......	......	......
Size of Air Preheater (sq. ft.)	......	65,200	46,800	......	......
Boiler Equipment	B. & W. Horizontal Longitudinal Drums	Combustion Engineering Ladd Vertical 5 Drum Bent Tube	Combustion Engineering Ladd Vertical 5 Drum Bent Tube	Edgemoor Horizontal Longitudinal Drums	Combustion Engineering Heine Vertical 4 Drum Bent Tube
Economizer Equipment	......	Foster Horizontal	Foster Horizontal	Foster Horizontal	Foster Horizontal
Superheater Equipment	B. & W.	......	......	......	......
Preheater Equipment	......	Combustion Engineering Plate Type	Combustion Engineering Plate Type	......	......
Water Wall Equipment	......	Combustion Engineering	Combustion Engineering	......	......
Boiler Baffling	Vertical 3 pass	Vertical 3 pass (each half)	Vertical 3 pass (each half)	Vertical 2 pass	Vertical 3 pass

traneous sources of error were a determining factor in the final selection of the cyclone and electric precipitator in preference to the other test methods of somewhat higher collection efficiency. Because, among other factors, it was soon found that by the use of these high-sampling-rate, constant-sampling-rate methods, the extraneous errors could be kept to a much lower value than when other test methods were used. The sampling errors referred to are (*a*) the error caused by not withdrawing a representative sample from the flue gas stream at the point of sampling, and (*b*) the error caused by withdrawing samples from points not representative of the true cross-sectional distribution of the dust loading in the flue gas stream. This latter source of error may be controlled by sampling from a number of different points in the gas stream cross-section so that the distribution of dust loading across the cross-section may be graphically visualized. In this respect, every flue constitutes an entirely new problem and there are, as yet, no rules for predetermining the type of distribution that will be encountered or the points from which samples should be withdrawn to get representative samples.

However, the error caused by not withdrawing a representative sample from the flue gas stream at the point being sampled, can be either eliminated or corrected. Several investigators (*8, 9, 22, 23, 24*) have proven that when the dust in the flue gas consists, as it always does, of an admixture of coarse and fine particles, the only correct way of withdrawing a sample of gas containing the coarse and fine in their proper proportion is to use a knife-edged sampling tip facing the direction of flow and having such a diameter that the velocity of the gas being sucked into the sampling tip will be the same as the velocity of the gas surrounding the sampling tip. If the sampling tip velocity is lower than the surrounding gas velocity, heavy particles from the surrounding gas will be thrown into the sampling tip by inertia causing a "sprinkled" or "peppered" sample indicating too high a dust loading, and vice versa. Fig. 5 shows the results obtained by four of these investigators, the difference in their curves being caused by the relative proportions of coarse and fine particles in the dusts studied. Every effort should be made to run tests at unity velocity ratio, but if this is not practical, a correction factor obtained from a curve of this type may be applied. Where corrections were necessary in Part II of this report, the dashed curve was used as giving an approximate correction. Fig. 6 from Zimmerman (*8*) shows in similar manner the errors caused by not having the sampling tip facing in the direction of the flue gas flow.

In order to keep the velocity ratio as near unity as possible, it is necessary to have a choice of several diameters of sampling tips which can be interchangeably used on the end of the sampling tube, and it is necessary to measure the flue gas velocity at the point to be sampled so that at any sampling rate the proper tip may be chosen. Several investigators have suggested methods by which an inclined-tube draft gage may be so connected to the sampling tip and an external pitot tube as to continuously indicate the velocity ratio. However, during the tests run in this investigation, it was found more convenient to separately measure the flue gas velocity, because it is possible to closely predetermine the sampling rate with both the cyclone and the electric precipitator and because it is not advisable with these methods to change the sampling rate during a test run.

TABLE IV—DATA DESCRIBING SAMPLING CONDITIONS

Boiler	A	B	C	D	E
Dimensions of Duct North Wall and South Wall	3′–6″ Diam.	4′–0″	9′–6″	13′–4″	10′–0″
East Wall and West Wall	......	8′–0″	7′–6″	2′–6″	4′–0″
Wall in Which Sampling Holes Were Drilled	North and east	North and west	North	South	East
Number Sampling Holes	2	2	1	3	2
Location of Sampling Holes	90° apart, north and east	36″ from no. wall 20″ from w. wall	60″ from west wall	25″, 50″ and 75″ from east wall	16″ from no. wall 16″from so. wall
Feet Above Nearest Disturbance to Gas Flow	4′	6′	6′	5′	4′
Disturbing Element	90° Bend	2 ID fan connections to duct	2 ID fan connections to duct	Damper and 90° bend	Cast iron economizer
Feet Below Nearest Disturbance to Gas Flow	3′	..	..	..	2′
Disturbing Element	Damper	..	..	..	Damper and 90° bend
Average Gas Velocity at Maximum Boiler Rating (ft. per sec.)	50	100	60	20	35

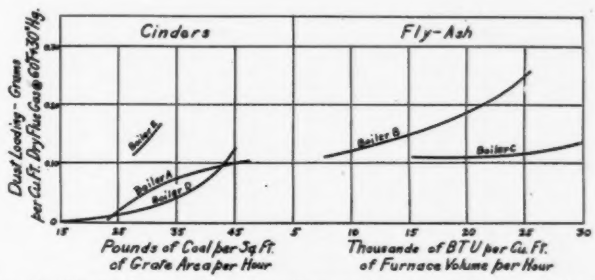


Fig. 8—Variation of dust loading at boiler outlet with boiler rating.

PART II

Results of Tests on Power Plants of Dust Loading and Properties of Cinders and Fly-Ash

Test Conditions. After the choice of the cyclone as a test method for practical power plant testing, it was necessary to prove this choice under the variety of conditions likely to be encountered. Therefore, tests were run on the five different boilers listed in Table III as representative of as wide a variety of test conditions as is likely to be met. The same general procedure was followed in testing each of these boilers. Samples were withdrawn from the nearest accessible duct to the outlet from the last bit of water or air heating surface in the steam generator. In the case of Boiler A, that sampling point was one of two cylindrical vertical uptakes from the third boiler pass. The flue gases rise vertically through the third boiler pass, leave the boiler setting through two horizontal ducts, are bent 90 deg. and enter the vertical uptake where samples were withdrawn. After passing the sampling point, the gases pass by a damper, and then successively through a horizontal settling chamber, a Green cindertrap, an induced draft fan and into the stack. In the case of Boilers B and C, the sampling point was the rectangular vertical duct leading from the two induced draft fans to the stack, the boiler, economizer and air preheater being ahead of the fan. In the case of Boiler D, the sampling point was the rectangular vertical duct

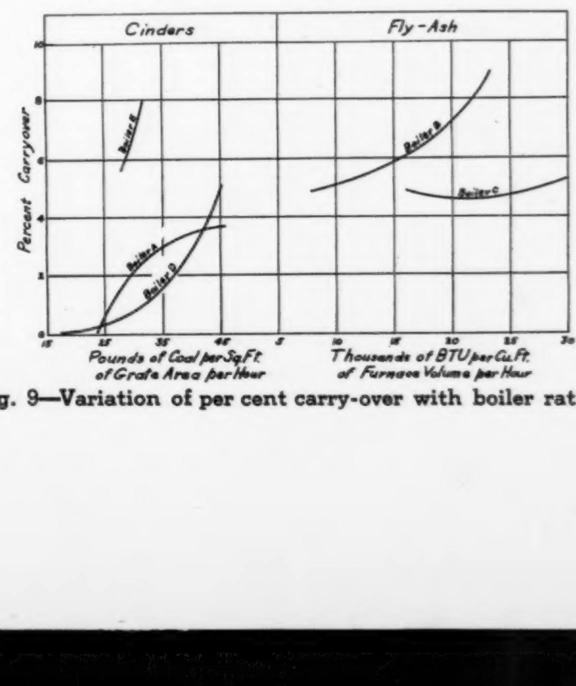


Fig. 9—Variation of per cent carry-over with boiler rating.

leading from the water-screen type cinder catcher to the induced draft fan. The flue gas in this boiler travels down through the boiler, then through a cast-iron economizer to the water-screen type cinder catcher where its direction is changed 90 deg. It then enters a duct containing a damper where its direction is changed another 90 deg. and from there it enters a vertical duct from which samples were withdrawn. During tests on this boiler, the water screen in the cinder catcher was not used. In the case of Boiler E, the sampling point was the short vertical rectangular duct connecting the cast-iron economizer outlet to the 90 deg. inlet bend of a Mumford type cinder catcher. The flue gases rise vertically from the last boiler pass, continue through the economizer, the cinder catcher, the induced draft fan and thence to the stack.

Thus it may be seen that not only were three different types of coal firing and three different kinds of fuel investigated, but that, excepting the similarity of Boilers B and C, each represented an entirely different type of sampling problem. It was necessary to obtain samples both before and after induced draft fans, before and after 90 deg. bends, before and after cinder catchers and before and after dampers. All pertinent data about the sampling conditions encountered in these ducts are summarized in Table IV. It must be noted, of course, that it was possible to take a number of different sampling points inside the uptake through one sampling hole and that the number and location of the sampling holes does not indicate the completeness or lack of completeness of the traverse of the duct cross-section. For most of this work, sampling holes made of 4-in. nipples, 4 in. long, welded to the duct, have proved satisfactory in allowing the use of large sampling tips and short diameter pipe bends.

Traverses of Ducts. In each of the five ducts described in Table IV traverses were made at one or more boiler ratings. Due to the disturbing conditions already noted, each duct had its own peculiar velocity distribution and cinder distribution across the cross-section. To reproduce all of these traverses in this paper, would be of no particular value because a cross-sectional traverse is only useful as a means to an end, the end being the average conditions for the duct arrived at by integrating the data obtained from the traverse. However, to show how this integration of traverse data is performed, the traverse data from the duct of Boiler A, for the specific condition of 40 lb. of coal per sq. ft. of grate area per hr., are reproduced as Fig. 7 (*a*, *b*, *c* and *d*). The following study of the four charts of Fig. 7 is indicative of the type of study that must be made of any set of traverse results.

The effect of the right-angle bend, through which the gases must pass before entering the uptake, in throwing the heavier particles toward the south wall is obvious from charts (*c*) and (*d*). The damper, past which the gases must pass before leaving the uptake, apparently has no effect upon this phenomenon. However, the effect of the damper is much more obvious in causing the peculiar velocity distribution of chart (*a*), although the effect of the right-angle bend is also

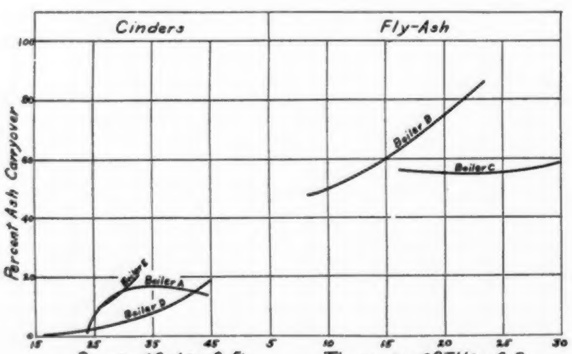


Fig. 10—Variation of per cent ash carry-over with boiler rating.

in evidence. The resulting distribution of dust-loading (chart *b*) is apparently a result of both the centrifugal concentration due to the right-angle bend and the velocity distribution caused by both the damper and the bend. It is obvious from a study

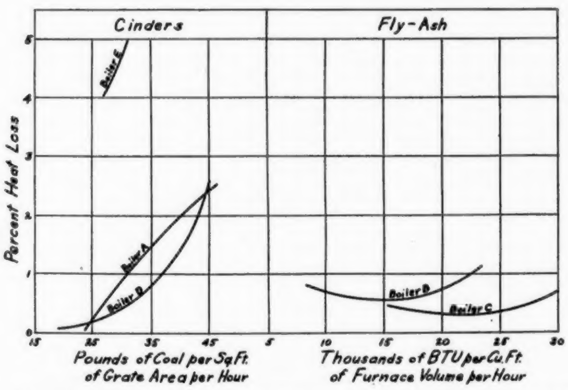


Fig. 11—Variation of per cent heat loss with boiler rating.

of these four charts that the use of any empirical method of traverse and sampling which does not allow both the individual weighing and sieving of a number of spot samples would have led to erroneous conclusions. However, by an evaluation of these four charts, with respect to one another, it is possible both to determine the weighted mean values of the four items represented and also to select the four single points in the uptake, where, for this particular boiler rating, these mean values occur. These mean values and their corresponding points along the north-south centerline are:

Chart	Mean Value	Point Where Mean Occurs—Inches South of East-West Centerline
a	46 ft. per sec.	4 in.
b	0.084 gram per cu. ft. of dry flue gas 60 deg. 30 in.	9 in.
c	55 per cent greater than 75 microns	10 in.
d	35 per cent greater than 150 microns	11 in.

In other words, the results of the traverse show that the mean dust loading at 40 lb. of coal per sq. ft. of grate area per hr. is 0.084 gram per cu. ft. and that this value could have been measured directly, with the other two subsidiary measurements in less than 10 per cent error, had a single spot sample been taken 9 in. south of the centerline. Unfortunately, it is only after testing, never before, that such interesting facts are known.

By obtaining data of this general nature over the whole range of useful boiler ratings for the five boilers tested, it has proved possible to examine the way in which dust loading and

TABLE V—COMPARISON OF SCREEN SIZES WITH SIZE IN MICRONS

Size in Microns	Inch	Nearest Fraction of an Inch	Nearest Sieve Size
1.0	0.000039	1/25,000	Hypothetical
5	0.000197	1/5,000	→(2,500)
10	0.000394	1/2,500	→(1,250)
20	0.000787	1/1,250	→ (600)
30	0.001181	1/833	Rare (400)
44	0.0017	1/588	325
74	0.0029	1/345	200
149	0.0059	1/169	100
177	0.0070	1/143	80
250	0.0098	1/102	60
297	0.0117	1/85	50
420	0.0165	1/60	40
590	0.0232	1/43	30
840	0.0331	1/30	20
2,000	0.0787	1/13	10

cinder characteristics respond to variations in boiler rating, type of fuel and method of firing. The remainder of this paper consists of results so obtained.

Dust Loading. Cinders are created primarily by the air blast through the coal bed on a stoker; therefore, cinder creation must be roughly proportional to the intensity of this air blast. The intensity of the air blast is in turn proportional to the rate of burning coal per square foot of stoker area. There-

fore, the rate of burning coal was chosen as the best unit for comparing the relative cinder creation at different ratings using dissimilar stokers and fuels.

Similarly, the best unit available for comparing fly-ash production in dissimilar furnaces was the rate of burning coal per unit volume of furnace. Unfortunately, this dual choice of units does not allow a direct comparison of stoker-fired and pulverized coal plants, but because of the fact that the pulverized coal-fired boilers tested had an average steaming capacity, about five times that of the stoker-fired boilers tested, and that the maximum boiler rating possible was about twice as great, it is evident that a comparison in terms of steaming rates or of boiler rating would be equally impossible.

The rate of increase of dust loading with increasing boiler rating is shown in Fig. 8. It must be borne in mind that this represents the dust loading leaving the boiler setting and is (*a*) smaller than the loading in the furnace by the amount of the dust deposited in the boiler passes and is (*b*) greater than the loading in the stack by the dust deposited in subsequent flues and dust collectors.

The apparent reason that the loading for E in Fig. 8 is so much higher than in A and D is because the coke breeze burned in E contained a much larger proportion of finer particles (Table III) than the anthracite fines in D and the coking bituminous in A. Note in these curves that the apparent characteristic of a chain grate stoker is an increasing rate of

TABLE VI—DUST DEPOSITED IN SOOT HOPPER—BOILER A

Boiler A Soot Hopper	Lb. of Coal per Sq. Ft. per Hour 24	32	40
% Carry-over	0.56	0.80	1.44
% Ash Carry-over	2.7	2.8	5.0
% Heat Loss	0.30	0.50	0.90

increase of dust loading at higher coal burning rates, whereas the apparent characteristic of an underfeed stoker is a decreasing rate of increase of dust loading at higher coal burning rates. Note also that the cinder loading at higher ratings becomes as large as the fly-ash loadings, although at lower ratings it falls off to practically nothing. These curves indicate that to keep cinder production from becoming excessive, coal burning rates for A and D should be kept below 25 lb. per sq. ft. per hr., and for E below 15 lb. per sq. ft. per hr.

TABLE VII—DUST IN FLUE GAS AT BOILER OUTLET—BOILER A

Boiler A Boiler Outlet	Lb. of Coal per Sq. Ft. per Hour 24	32	40
% Carry-over	0.10	2.65	3.25
% Ash Carry-over	1.0	18.0	15.0
% Heat Loss	0.05	1.15	1.95

Of course, in practical operation, the solution is to run at a much higher coal burning rate than these with a cinder catcher to reclaim the cinders and return them to the furnace for reburning.

The fly-ash curves of Fig. 8 indicate that the tangentially

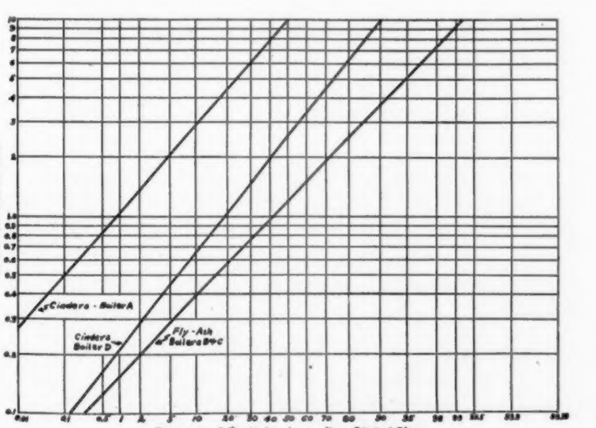


Fig. 12—Size-frequency distribution of cinder and fly-ash particles.

fired boiler (C) has an almost constant dust loading at all ratings, whereas the dust loading in the vertically fired boiler (B) increases with rating. The slope of this curve (Boiler B) is, however, believed to be somewhat steeper than it should be, due, possibly, to sampling errors.

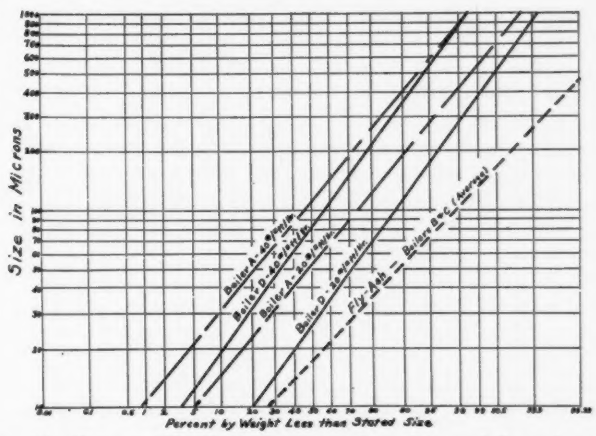


Fig. 13—Size-weight distribution of cinder and fly-ash particles.

It is possible to use this dust loading data of Fig. 8 as the basis for calculated data which are much more easily interpreted in terms of operating results. In order to effect these calculations the following data must be available for each test run:

D—Dust loading in grams per cubic foot of dry flue gas at 60 fahr.–30 in. Hg.

δ—Density in pounds per cubic foot of dry flue gas at 60 fahr.–30 in. Hg.

P—Pounds of dry flue gas per pound of coal fired.

A—Per cent ash content of coal as fired.

S—B.t.u. per pound of coal as fired.

C—Per cent loss of weight on ignition of cinders or fly-ash sample.

R—B.t.u. per pound of combustible in cinders or fly-ash.

Of these δ, P, A and S may be obtained directly or calculated from the coal analysis and the analysis of the flue gas in the flue from which the dust sample was withdrawn. C is obtained by burning a portion of the dust loading sample. R is obtained either from a bomb calorimeter or from an approximation. From these data, the following calculations may be made:

(*a*) Per cent carry-over—which is the weight of the dust as a per cent of the weight of the coal fired.

$$\text{Per cent carry-over} = \left(\frac{0.2205\ DP}{\delta}\right)$$

(*b*) Per cent ash carry-over—which is the weight of the ash content of the dust as a per cent of the weight of the ash in the coal fired.

$$\text{Per cent ash carry-over} = \left(\frac{0.2205\ DP}{\delta}\right)\left(\frac{100\text{-}C}{A}\right)$$

(*c*) Per cent heat loss due to cinders or fly-ash as a per cent of the heat in the coal fired.

$$\text{Per cent heat loss} = \left(\frac{0.2205\ DP}{\delta}\right)\left(\frac{CR}{100\ S}\right)$$

The curves of per cent carry-over and ash carry-over (Figs. 9 and 10) have the same general trend as the dust loading curves (Fig. 8) but they are easier to understand, and, hence, are more useful curves. Note particularly the difference in per cent ash carry-over between the cinders and fly-ash groups and also that the fly-ash curves show the per cent of ash retained by the pulverized coal furnace as compared with the percentage discharged in the flue gas. In connection with these curves, it would seem as though the use of per cent carry-over or per cent ash carry-over, preferably the former, would offer a more

logical method of expressing maximum permissible legal limits of cinder and fly-ash emission than the proposed use of a maximum permissible dust loading. Curves of this nature (Fig. 9) show clearly what limits are and are not possible of attainment by the use of dust collectors of reasonably low first cost having overall collection efficiencies of about 75 per cent.

Heat Loss Due to Cinders and Fly-Ash. Curves of per cent heat loss due to cinders and fly-ash, computed as has been indicated, are shown in Fig. 11. Of particular interest in these curves is the magnitude of the loss, amounting, as it does, to a large proportion of the normal radiation and unaccounted for losses; and, in some cases, being larger than the normal moisture, carbon monoxide or ash pit losses, which are invariably measured in boiler tests. Of interest, also, is the fact that the data for Fig. 11 were obtained by a method easily applicable to routine boiler testing.

Particle Size Distribution. Perhaps the least known but most important characteristic of flue dusts are their true size distribution. Most of the size distributions appearing in the literature of the subject do not represent the true size of the material suspended in the gas leaving the boiler setting, but rather represent the sizing of material collected from flues, passes and dust collectors because these have generally been the only samples available in large enough quantity to be analyzed for size distribution. However, the samples collected during this investigation by cyclone and precipitator, representing as they do over 95 per cent of the total gas suspended

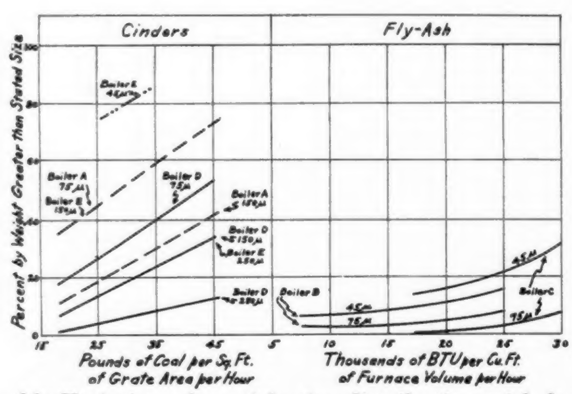


Fig. 14—Variation of particle size-distribution with boiler rating.

dust loading, were all analyzed for size distribution in the following manner:

Samples from Boilers B, C, D and E were sieved through a series of Tyler sieves, the finest being 325 mesh, using a Ro-Tap machine. Samples from Boiler A were hand sieved, the finest sieve for most of the samples being 200 mesh. A portion of each sample was, before sieving, placed in one of three composite samples representing either Boiler A, Boilers B and C or Boiler D. No composite sample was made of Boiler E. Several microscope slides were made from each of the composite samples by dispersing the sample using diacetone alcohol (*25*). Size-frequency measurements were made from these slides using a Zeiss filar micrometer at about 700 dia. magnification, 200 or more particles being measured on each slide. Size-frequency distributions were calculated from these data and plotted on Codex logarithmic-probability paper according to the method of Hatch and Choat (*26*). The slopes of these size-frequency distribution curves were then used to determine the slopes of the curves of the sieve sizing, also plotted on logarithmic-probability paper according to the method of Hatch (*27*) with the exception that the displacement of the size-weight curves from the size-frequency curves was not calculated, but was the result of experimental data.

The size-frequency curves so obtained are shown in Fig. 12 and serve to show the fundamental difference between the dusts produced by the three methods of burning coal. The size-weight distribution curves are shown in Fig. 13. Table V is included to show the relation between sieve sizes and sizes expressed in microns. (A micron equals one-thousandth of a millimeter.) Note on Fig. 13 the increase in particle size of

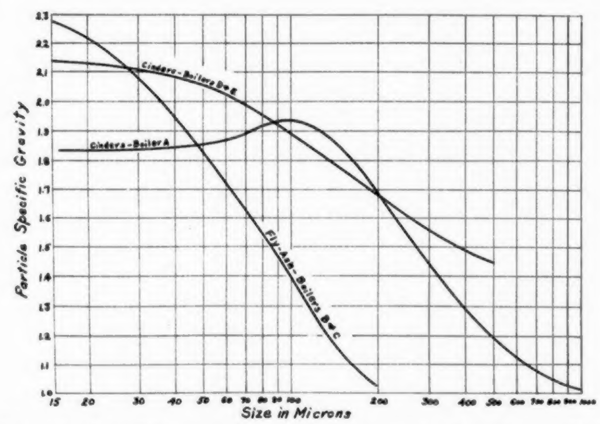


Fig. 15—Specific gravity of cinder and fly-ash particles.

the samples at 40 lb. of coal per sq. ft. per hr. compared with those at 20 lb. This increase in size with rating is more clearly shown by Fig. 14 which also includes some data from Boiler E. The slope of the fly-ash curves of Fig. 14 is probably too steep because of velocity-ratio inequality during the withdrawal of several of these samples.

Size-frequency curves obtained by use of a cyclone may be in error to the extent that a definite amount of particle breakage may occur in the collector by virtue of collisions between particles themselves and between the particles and the collector. Experimental data on collection of materials, other than cinders and fly-ash, indicates that this size degradation may cause as much as a 25 per cent drop in the mean particle size. However, in spite of this knowledge, it is felt that the degradation in the recommended design of cyclone is small enough so that the size-frequency curves directly derived from collected samples may be used for all practical purposes.

Particle Specific Gravity. The dust remaining on each of the sieves for each of the boilers was separately studied for specific gravity to determine the relationship between particle size and particle specific gravity for each of the methods of burning coal. Specific gravity was determined using a water filled pycnometer and represents the weight of a particle of unit volume. This should not be confused with either the specific gravity of the material composing the particle, which will tend to be greater because of the porosity of the particle, or the bulkiness of a unit volume of particles, which will be less because of the voids between particles.

The relationship between specific gravity and particle size is shown as Fig. 15. The similarity between the curves for Boilers A, D and E are noteworthy as is the rapid decrease of specific gravity with increasing size of fly-ash particle. Specific gravity determinations were also made of composite samples at various boiler ratings. These are shown as Fig. 16

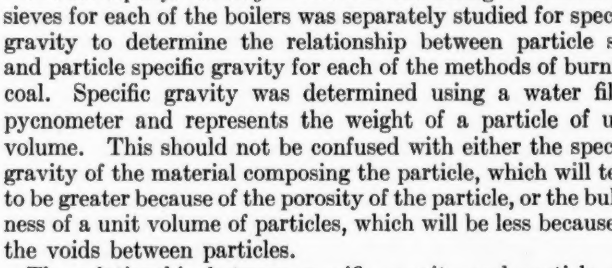


Fig. 16—Variation of mean particle specific gravity with boiler rating.

and may be analyzed by means of its two component curves Figs. 14 and 15.

Combustible Content of Particles. A number of samples were chemically analyzed for "loss of weight on ignition" for three reasons, (*a*) to obtain a value for computing the per cent heat loss due to cinders or fly-ash using the assumption that "the loss of weight on ignition" represents combustible matter only, (*b*) to help explain the variation of specific gravity with particle size, and (*c*) to classify particle size groups according to the method of formation of the particles as indicated by their resulting combustible content. For the two latter purposes, Fig. 17 was obtained. Comparing this with Fig. 15 shows that, as would be expected, specific gravity varies directly with the ash content of the particle, i.e., inversely with combustible content. The extremely porous nature of fly-ash cenospheres is indicated by their relatively low specific gravity in spite of a high ash content. The smooth and gradual variation of fly-ash properties with particle size indicates that the only reason for this variation must be that during their passage through the furnace the larger particles are not burned out as completely as the finer particles. Similarly, the smooth and gradual variation with particle size of the cinder properties from Boilers D and E indicates that all size ranges of particles must have been produced in the same general manner—the physical blowing over of fine coal and ash particles—and that, similar to fly-ash, the only reason for the variation in properties must be that during their passage through the furnace the larger coal particles are not burned out as completely as the finer particles.

The origin of the particles from Boiler A appears to be somewhat different as is indicated by the peculiar variation of properties with particle size. This variation has been checked by means of studies of the properties of cinders removed from passes, flues and dust removers associated with this boiler, which have indicated a similar trend of properties. The conclusions drawn from these data have been checked by visual examination of the particles. The particles over 300 microns are small coke particles. Most likely these particles were blown from the grates as small coal particles and coked during their rapid passage through the furnace, so that most of the available oxygen was used to burn the volatile matter, thus allowing the fixed carbon to leave the combustion zone largely unconsumed. The particles between 100 and 300 microns were most likely blown from the grates as small coke fragments, thus allowing them to be fairly well burned out during their passage through the furnace. The particles below 100 microns, are believed to be a heterogeneous admixture of (*a*) soot particles, (*b*) inherent ash released from the coal and coke during its burning, and (*c*) smaller particles of the coal and coke fragment

TABLE VIII—TOTAL DUST PRODUCED IN FURNACE—BOILER A

Boiler A	Lb. of Coal per Sq. Ft. per Hour		
Furnace Total	24	32	40
% Carry-over	0.66	3.45	4.69
% Ash Carry-over	3.7	20.8	20.0
% Heat Loss	0.35	1.65	2.85

type. The relatively high combustible content is believed to be due to the high soot content.

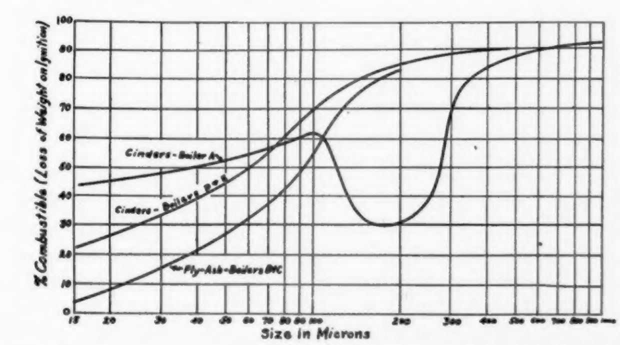


Fig. 17—Combustible content of cinder and fly-ash particles.

In general, these curves indicate that the size range of particles most easily caught by a moderately efficient cinder catcher (the larger particles) are the ones most valuable to reclaim for reburning. Figure 18 shows the variation of com-

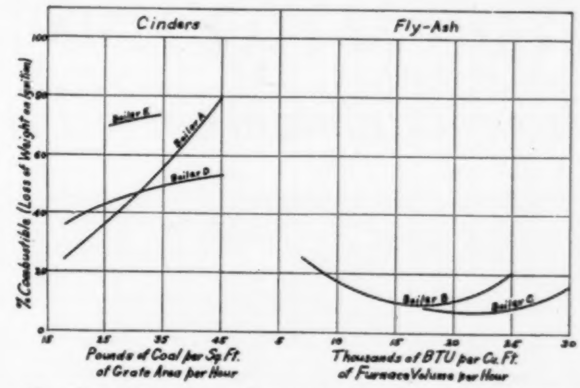


Fig. 18—Variation of combustible content with boiler rating.

bustible content with boiler rating and may be analyzed by means of its two component curves, Figs. 14 and 17. This curve is useful for computing the per cent heat loss due to cinders or fly-ash.

Summary of Test Results

The test results presented in this paper have been obtained from too few different plants to be considered as truly representative of the three basic coal burning methods. However, the fundamental differences and similarities between the three are clearly indicated. The reason for obtaining this collection of data has been solely to show that the recommended test methods for cinders and fly-ash are capable of yielding satisfactory and useful results. The primary object throughout has been to test the test method, rather than to test the plant.

PART III

Study of Cinder Deposits in Boiler Passes

As has been explained, the dust loadings and all other derived data given in Part II were obtained from the flue gases leaving the last portion of heating surface of the steam generator. Therefore, these loadings must be less than the loading produced by the furnace by the weight of dust deposits in the steam generator itself. These dust deposits in the steam generator must be removed from time to time to keep the draft drop below what it would be if they were allowed to accumulate. In vertically baffled boilers, the usual two types of deposit encountered are (*a*) a heavy particle deposit at the bottom of the second boiler pass and (*b*) a soot and very fine particle deposit on boiler and economizer tubes. The common misnomer for the hopper built to catch the former type is "soot hopper" or a somewhat more applicable term "back connection." This hopper may, as in the case of Boiler A, be arranged to dump intermittently into cars spotted on the ash pit level; or, as in Boiler E, have continuous removal by means of a screw conveyor; or, lastly, as in Boiler D (a two-pass boiler) it may be equipped with water sprays and baffles for use as a cinder catcher. The soot deposits on boiler and economizer tubes are removed by blowing them into the flue gas stream by steam jets. No quantitative measure of this latter form of soot deposit is possible, although it may be qualitatively estimated by measurements of boiler outlet dust loadings during soot blowing. Although this was not done during these tests, it is reasonable to assume that the weight of material blown from the tubes is small compared to the weight of the hopper collection.

Deposits in Soot Hopper—Boiler A. The weight of cinder collected in the soot hopper of Boiler A alone was calculated

by weighing the removals from three separate identical boilers after having run these boilers at constant rating for about two days each for each of three different boiler ratings. After weighing these cinders were sampled for combustible and other similar determinations. This allowed the calculations of Table VI. This table shows that the cinder deposit in the soot hopper increases with coal burning rate, as does the heat loss due to these cinders. Table VI, representing the soot hopper cinders, must be added to Table VII representing the boiler outlet dust loading (from Part II of this report), to determine Table VIII, the total dust produced by the boiler furnace. It should be noted that at a coal burning rate of 24 lb. per sq. ft. per hour, the cinder removal from the soot hopper is considerably greater than the boiler outlet loading and that this condition is reversed at higher coal burning rates. This is most likely caused by the low gas velocity at the low boiler rating, which allows the bulk of the cinders to settle out of the flue gas into the soot hopper. At the two higher ratings, the per cent carry-over and similar derived data for the soot hopper are roughly one-third of that measured in the boiler outlet. In other words, in Boiler A, about one-fourth of the cinders produced by the furnace are caught in the boiler passes; about three-quarters leave as gas suspended dust loading. In Table VIII, the magnitude of the maximum values are noteworthy—carry-over approaches 5 per cent, ash carry-over equals 20 per cent and heat loss approaches 3 per cent.

Similar weighed removal tests were not run for any of the other boilers, but observation of the removal from Boiler D and E would indicate a very similar situation. The size-weight distribution of the soot hopper removals of Boiler A, is shown in Table IX. It is considerably coarser than the boiler outlet dust. The sizing of the removal from Boiler D and E is somewhat coarser than this. The average combustible content of the removal from Boilers A, D and E are respectively: 73, 81 and 89 per cent. The average specific gravity of the removals from D and E are respectively: 1.71 and 1.59. In order to estimate the size of bins to hold cinders or the weight of a known volume of cinders, the specific bulkiness is of interest. For the removals from A, D and E, respectively, this has values of 0.33, 0.57 and 0.50.

TABLE IX—SIZE-DISTRIBUTION OF DUST (BY WEIGHT)—BOILER A—SOOT HOPPER

Boiler A—Soot Hopper Size, Distribution, Size in Microns	Lb. of Coal per Sq. Ft. per Hour 24	32	40
1st Quartile Size	250	300	360
Median Size	410	500	640
2nd Quartile Size	660	800	980

Conclusion

Cinder and fly-ash from power plants represent both a nuisance to the public and a loss to the plant. There are only two possible ways of stopping this emission; either by not producing any in the furnace, or, if some are produced in the furnace, by not allowing any to escape out of the stack. The first method of attack is generally not a practical one; therefore, resort must be made to the latter method. For intelligent operation and design of plants using the latter method of control, test methods adaptable to routine testing must be available as must data to which these routine tests may be compared. The purpose of this paper has been to offer such a test method and its derived data.

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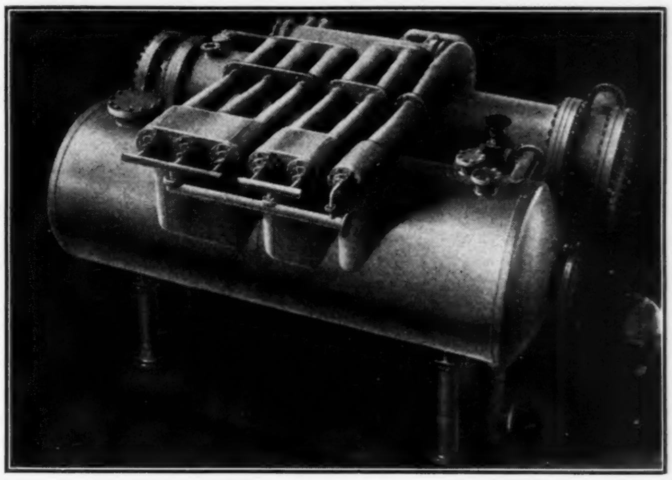
The American Society for Testing Materials will hold its Thirty-Sixth Annual Meeting at The Stevens Hotel in Chicago the week of June 26th. Among the papers scheduled to be presented at this meeting which will be of interest to COMBUSTION'S readers are the following:

"A Study of Adsorption as a Method for the Determination of the Surface of Pulverized Coal" by R. A. Sherman, C. E. Irion and E. J. Rogers.

"Agglutinating Value Test for Coal" by W. A. Selvig, B. B. Beattie and J. B. Clelland.

"Consistent Data Showing the Influence of Water Velocity and Time on the Corrosion of Iron" by R. F. Passano and F. R. Nagley.

"Corrosion Resistance of Structural Aluminum" by E. H. Dix, Jr.



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